UCRL-TR-213355

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Sensor Acquisition for Water Utilities: Survey, Down Selection Process, and Technology List

Maureen Alai, Lee Glascoe, Adam Love,
Mackenzie Johnson, Wayne Einfeld

June 30, 2005

Disclaimer

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Sensor Acquisition for Water Utilities:

Survey, Down Selection Process, and Technology List

Maureen Alai, Lee Glascoe[1], Adam Love, Mackenzie Johnson
Lawrence Livermore National Laboratory
Livermore, CA

Wayne Einfeld[2]
Sandia National Laboratories
Albuquerque, NM

UCRL-TR-213355/SAND2005-2671P/SAND2005-4191
Original Release: April 29, 2005
Amended Release: June 30, 2005
Final Upload: August 19, 2005

Auspices & Disclaimer
Funding for this effort is provided by the US Department of Homeland Security Directorate of Science and Technology as a part of the Chemical Countermeasures Portfolio. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

1 Executive Summary

The early detection of the biological and chemical contamination of water distribution systems is a necessary capability for securing the nation's water supply. Current and

---

[1] 925-423-2922, glascoe1@llnl.gov
[2] 505-845-8314, weinfel@sandia.gov

emerging early-detection technology capabilities and shortcomings need to be identified and assessed to provide government agencies and water utilities with an improved methodology for assessing the value of installing these technologies. The Department of Homeland Security (DHS) has tasked a multi-laboratory team to evaluate current and future needs to protect the nation's water distribution infrastructure by supporting an objective evaluation of current and new technologies. The LLNL deliverable from this Operational Technology Demonstration (OTD) was to assist the development of a technology acquisition process for a water distribution early warning system. The technology survey includes a review of previous sensor surveys and current test programs and a compiled database of relevant technologies. In the survey paper we discuss previous efforts by governmental agencies, research organizations, and private companies. We provide a survey of previous sensor studies with regard to the use of Early Warning Systems (EWS) that includes earlier surveys, testing programs, and response studies. The list of sensor technologies was ultimately developed to assist in the recommendation of candidate technologies for laboratory and field testing. A set of recommendations for future sensor selection efforts has been appended to this document, as has a down selection example for a hypothetical water utility.

2 Introduction

The security of our nation's water distribution systems is a major concern since the events of September 11, 2001. Prior to that time, water contamination concerns were primarily in regard to natural events and accidental contaminant release while intentional threats were considered fringe events (Brosnan, 1999). A notable exception, however, was the US Air Force concern of intentional contamination/destruction of military water distribution systems (Hickman, 1999). After September 2001, the protection and safety of municipal, private and military water distribution systems from intentional contamination has become a priority to ensure an uninterrupted supply of drinkable water to the public in adequate quantities and under adequate water pressure to satisfy public health, firefighting, and industrial needs. It is to satisfy the needs of the water utilities in their mission of serving the public with a safe water supply that we have based this water monitoring sensor survey and technology-acquisition strategy presented below.

While it has been understood for some time that environmental contamination of water distribution systems is a threat to the mission of the water utilities (ASCE, 2004), it has been identified by the Environmental Protection Agency and the National Research Council (2003) that water distribution systems are vulnerable to deliberate contamination in part because there are many readily available access points. The prevention and detection of intentional contamination events are directly relevant to previous and ongoing efforts at preventing and detecting unintended or natural contamination events. Consequently, efforts concerning intentional contamination must leverage off of and contribute to efforts concerning accidental and natural releases. Many threats and vulnerability assessments to US water systems have focused primarily on unintended and/or natural contamination. The US Air Force (Hickman, 1999), the US Environmental Protection Agency (EPA, 2004), the Kansas Department of Health and Environment (2003), the Susquehanna River Basin Commission (2004), the American Water Works Association (Schreppel, 2003), the American Society of Civil Engineers

(ASCE, 2004), and De Young and Gravely, 2002 are a just a few of the military, federal, state, local, and privately funded studies that have recently examined these threats. Early Warning Systems, EWS, the focus of many these studies, is defined as an integrated system consisting of monitoring technology, analysis and interpretation, and, ultimately, decision-making for protecting public health while minimizing unnecessary concern and inconvenience within a community (Hasan et al, 2004).

Water utilities can address the threat of deliberate contamination through improved physical security and water monitoring and emergency response planning and execution. Implementation of water monitoring capabilities begins with the non-trivial process of sensor selection. In this document we present a survey of previous and on-going studies of EWS sensor technology that is followed by a discussion of options and constraints to be faced by water utilities when choosing an EWS sensor technology for their distribution system. Based on discussion with members of the DHS Operational Technology Demonstration Project Advisory Board (consisting of representatives from the EPA, AWWA, DHS, NASA and individual water utilities) and on the literature, we have assembled a list of the most important parameters affecting water utilities' choice of sensor technology. These parameters allow us to create a list of ranked criteria to assist sensor selection decisions faced by water utilities when designing a water-distribution monitoring system including sensor selection, sensor testing, sensor placement, and alarm response (detect-to-warn or detect-to-treat).

3 Water Monitoring Sensor Technology Survey

3.1 Review of Technology Surveys

We identified several different agencies and their reports detailing and evaluating the design of online water monitoring warning systems, and we found a commonality of issues within all of the reports. For online monitoring systems, each report listed similar needs for EWS, such as the following:

- The identification of surrogate water quality parameters as the best approach for distribution system monitoring for contamination events.
- The need for a clear understanding of the normal variability of baseline water data to aid in the interpretation of surrogate water quality data during a contamination event.
- The understanding that distribution system contaminant transport modeling is an important component of an overall EWS design architecture.
- The need to determine the objective of an EWS in terms of detect-to-warn and detect-to-treat.
- The need for established emergency response protocols and procedures.
- The development of advanced water monitoring sensors that can meet cost, reliability and performance parameters identified generally by the water utility industry and specifically by individual utilities.

The pathway to meeting these needs is not straightforward and is continually evolving. Listed below and tabulated in Table 1 are the findings from each report detailing previous efforts of different agencies.

ILSI Report (1999)

The International Life Sciences Institute (ILSI) published in 1999 their workshop findings focusing on three specific areas: (1) threats to drinking water supplies from low probability/high public health impact events; (2) early warning monitoring approaches; and (3) interpretation, risk management, and public communication issues. The report reflects the expertise of scientists from government, industry, academia, and the public interest sector and presents a concise assessment of (1) threats, (2) vulnerability, (3) EWS requirements, (4) EWS design, (5) the of monitoring chemical, radioactive, and microbial contaminants, (5) data interpretation, and (6) emergency response.

AwwaRF (2002)

In 2002, the American Water Works Association Research Foundation (AwwaRF) published extensive findings from a study of online monitoring for drinking water utilities which was funded by AwwaRF and the Italian Public Services Research Council (CRS PROAQUA). This study identified the following needs: (1) the need for online monitoring; (2) the need for specifications and testing of online monitors; (3) the need for proper selection of online monitoring equipment; sensors to monitor physical, inorganic, organic, biological, flow, level, and pressure parameters; and (4) the need for proper data handling and validation. Detailed and specific information is presented in this report for each of the different technologies used to monitor water quality and distribution system conditions.

ASCE (2004)

The American Society of Civil Engineers (ASCE) prepared the WISE Report in 2004 that provides comprehensive analyses and guidelines for designing an online contaminant monitoring system. The report covers several relevant topics including (1) a discussion of the contamination problem, (2) a rationale for online monitoring, (3) system design basics, (4) the use of contaminant lists, (5) the importance of detection limits, (6) the selection and placement of instruments and platforms, (7) data analysis and the use of models, (8) communication system requirements, (9) responses to contamination events, (10) the need to interface with existing surveillance systems, and (11) operations, maintenance, upgrades, and exercises of the system.

Table 1. Previous Design Standards and Surveys

Study	Comments	Reference
ILSI Report	Pre September 11 concerns	ILSI, 1999
AWWA Report	AWWARF, CRS PROAQUA	AWWA, 2002
ASCE WISE Report	M&C Subcommittee Design Guidance and Survey	ASCE, 2004
KIWA Report	Report-of-Technology	Kiwa, 2004
EPA/NHSRC	Research Action Plan	EPA, 2004
AWWA Report	Water Utility Perspective	AWWA, 2005

AwwaRF, Kiwa (2004)

In close collaboration, AwwaRF and Kiwa (a Dutch water research organization) conducted the Early Warning Monitoring project and presented the results in a 2004 final draft report titled *Early Warning Monitoring in the Drinking Water Sector*. This document details an effort to develop an overview of sensor development and identifies the developments that are potentially applicable as early warning techniques: (1) criteria for the prioritization of contaminants; (2) results from several transport modeling studies that were used to examine the spread of a contaminant through a water supply and evaluation of the boundary conditions for an effective EWS; (3) criteria for selection of an early warning system; (4) detection techniques for chemical priority agents; and (5) early warning systems (EWS) selected for further evaluation. The contaminant transport modeling studies highlight the necessity of hydraulic modeling to assist with the determination of network contamination and the relationship between the number of sensors and the overall impact of a contamination event.

EPA (2004)
The 2004 EPA report *Water Security Research and Technical Support Action Plan* EPA/600/R-04/063, identifies important water security issues, describes research and technical support needs, and presents a list of relevant projects responsive to these concerns. This action plan was developed in collaboration with the National Homeland Security Research Center (NHSRC), the Water Security Division (WSD), their federal partners, and various stakeholders.

AWWA (2005)
In early 2005, AWWA convened a Utility Users' Group Workshop to discuss and evaluate the security issues that are of prime concern to water utilities. A written report discusses the perspective and evaluations of chemical warning systems, contamination indicators, data transmission and analysis, alarms and/or triggers, and response. From this effort, recommendations and questions were generated for improving the overall security of water distribution systems.

The important points gleaned from our survey in regard to sensor selection criteria are the following:

1. Because the desired sensors are non-specific, it is necessary to require a detect-to-treat system where a sensor alert would trigger a sample to be collected and held for collection and thorough analysis at a traditional laboratory.
2. It will be important to understand and characterize the sensor responses to normal changes in the water system quality in order to minimize the false positive occurrences and ensure adequate sensitivity to alert when water quality parameters exceed normal baseline conditions.
3. It is critical to understand baseline water quality under all possible normal conditions such as changes in source water, disinfection, seasonal and system temperature changes.

3.2 Review of Sensor Testing

To determine if a developed sensor is appropriate for a particular application, the sensor performance needs verification by laboratory- and field-testing to determine whether or not the sensor's sensitivity and accuracy is appropriate for the proposed application. A deployable sensor must be able to provide useable data, and it must be able to detect a sudden relative change in concentration over a baseline value. In the case of surrogate measures, it is the change in the system that indicates a potential problem (ASCE, 2004).

Several of the current commercially available sensor systems measure surrogate parameters (e.g., physical parameters such as temperature, turbidity, conductivity, pH, total organic carbon) rather than measuring a specific contaminant. By using surrogate parameters, the presence, identity, and concentrations of contaminants are inferred from measurements of other properties in the water. While the data from the surrogate measures may be reliable and accurate, the connection between the measured surrogate parameters with the identity and concentrations of a specific contaminant is difficult to establish (ASCE, 2004).

Table 2. Sensor Testing and Evaluation Programs

Testing Agency	Testing Program	Comments	References
EPA	Environmental Technology Verification (ETV) Advanced Monitoring Systems Center	Voluntary vendor participation, chem./bio, stakeholder oversight, bench-scale & field-scale	Technical Contact: Eric Koglin
EPA	Technology Testing and Evaluation Program (TTEP)	Involuntary vendor participation, under preparation	EPA, 2005 Technical Contact: Eric Koglin
ECBC	Development and Engineering Center	Water-Pipe-Loop testing for chem/bio agents	Technical Contact: Alex Pappas

Several testing programs such as the EPA's Environmental Technology Verification (ETV) Program, EPA's Technology Testing and Evaluation Program (TTEP), and the Development and Engineering Center program at the Edgewood Chemical Biological Center (ECBC) evaluate sensor performance. These programs include bench-top and water-pipe-loop testing (see Table 2). To complement the efforts of these three programs, additional sensor testing is needed to correlate sensor surrogate parameters with specific contaminants and with chemical classes of contaminants. Additionally, sensor-response under the highly variable conditions of actual water distribution systems is currently not being measured in these testing programs. The varying conditions include different disinfection systems (e.g. chlorine vs. chloramines), changes in source water (e.g., ground water vs. surface water), and changes in seasonal and system temperature. Individual water utilities could make better informed sensor acquisition decisions if this additional data were available and accessible.

3.3 Review of Sensor Placement

Sensor placement is of concern to the water utilities as it involves planning and analysis, and has costs associated with the purchase, maintenance, and operation of individual sensors. Sensor placement should be based on an analysis that both (1) minimizes a contamination-event's impact on public health and (2) helps to identify emergency response and decontamination locations. Analysis of the distribution network, vulnerability assessment, threat analysis, and water usage are all components relevant to properly locating sensors within an EWS (Hasan et al, 2004). Additional physical requirements warranting consideration include sensor-cost, physical access to installed sensors, space limitations, infrastructure compatibility with sampling methods, access to power supplies, physical site security, and hydraulic conditions (ASCE, 2004). Hydraulic distribution modeling during the design process can help to resolve many of these issues.

3.4 Hydraulic and Contaminant Transport Modeling of Distribution Systems

Since water distribution systems involve a large number of unknowns, numerical models of water-flow and contaminant-transport such as EPANET (Rossman, 2000) are often employed to help site hydraulic equipment and sensors. These models are also used in the consideration of optimal sensor deployment and for the analysis of potential and actual threats (e.g., the EPA TEVA Program employs the EPANET model with a stochastic ensemble approach, Murray, 2004). To use these tools, water utilities develop a hydraulic model of their distribution system typically based on the standard pipeline network models like EPANET (Rossman, 2000), WaterCAD (Haested Methods, 2002), and PipelineNET (SAIC, 2003).

Preparation of the distribution system is the most critical and time-consuming step in running these models. By combining the details of the network infrastructure, such as the location and size of the pipes, valves, connections, pumps, and pipeline roughness with a history of water inflow and outflow, a utility can track the movement of a contaminant within the pipeline-network with a reasonable degree of accuracy. Once the lay-out of a distribution system and its associated flows and withdrawals are known, contaminant-transport modeling within the pipeline network models can identify the spatial spread of contamination over time at different release points and can, thus, assist in sensor placement decisions (e.g., Uber et al, 2004; Hasan et al, 2004; KIWA, 2004; ASCE, 2004; Glascoe, 2004; Murray, 2004). A simple example of a small and closed water distribution system demonstrates the utility of a hydraulic model in guiding the placement of sensors. If the contaminant enters the system upstream and the sensors are located downstream, early warning of a large downstream population could potentially be carried out (Figure 1). If a contaminant enters the system downstream of the sensor locations, the sensor would not detect the contaminant due to direction of water flow and the utility would consequently have a diminished early warning capability (Figure 2). Site-specific network models help to identify the relative importance of detecting low contaminant concentrations spreading through a large part of the distribution system (as in Figure 1), versus the importance of a rapid response capability to quickly identify larger toxic contaminant loadings limited to a specific region of the distribution system (as in Figure 2). More informed tradeoff decisions in sensor acquisition and deployment are available thanks to the network analysis to balance the cost of sensor placement with potential consequences. The hydraulic models also allow water-utilities to improve their pipeline system where necessary in order to optimize sensor placement decisions and to coordinate emergency response.

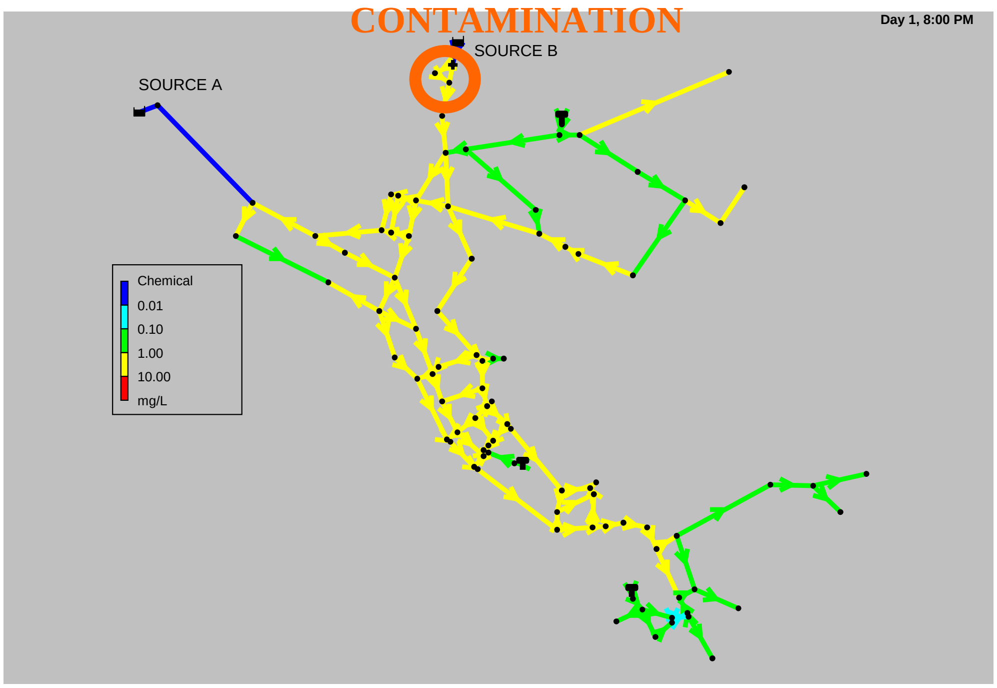

Figure 1. A hypothetical water distribution system experiencing a wide dispersal of low contaminant concentrations (modeled using EPANET in Glascoe, 2004).

3.5 Review of Response to Sensor Alarm

Deployed sensors should alert the water utility to changes in the water system and, ultimately, should assist the utility in its emergency reaction and response. To be a useful device, the sensitivity of the sensor must exceed the baseline water quality parameters. To minimize cost and to reduce public skepticism, it is necessary for a sensor to have minimal false-positive and false-negative responses, which requires an understanding of the specific baseline water quality of the distribution system for all normal operating conditions (ILSI, 1999). Necessary baseline water quality conditions will vary from utility to utility as baseline conditions are affected by changes in source water, disinfection systems, and seasonal and system temperature/pH.

3.5.1 Detect-to-warn versus Detect-to-treat

As part of an EWS, the response to a contamination event can fall into two types: *detect-to-warn* or *detect-to-treat* systems. Detect-to-warn systems employ sensors with sampling and detection times of a few seconds to a few minutes, whereas, a detect-to-treat system employ sensors with sampling and detection times of a few minutes to a few hours. Detect-to-warn systems are intended to prevent or minimize contaminant exposure to the population. Detect-to-treat systems attempt to identify the specific contaminant so that appropriate medical treatment and decontamination can be rapidly implemented. The current state of sensor technology and control over water distribution systems limits the type of EWS response that can be implemented. However, sensor technologies and control systems are being developed that could improve response times (e.g., Battiston et al, 2001; Emili and Cagney, 2000; Hergenrother et al, 2000; Lang et al, 1999; Marshall and Hodgson, 1998). Emergency preventive action will be successful only if there exists a high degree of confidence in sensor results. Such confidence requires a reduction in the likelihood of false positives. An additional impediment to true detect-to-treat systems is the costly infrastructure requirements for implementing a response system: a thorough detect-to-warn system would require a 24-hours-a-day, 7-days-a-week staffing of an emergency response center where staff can rapidly evaluate the real time sensor data streams to make appropriate emergency response decisions.

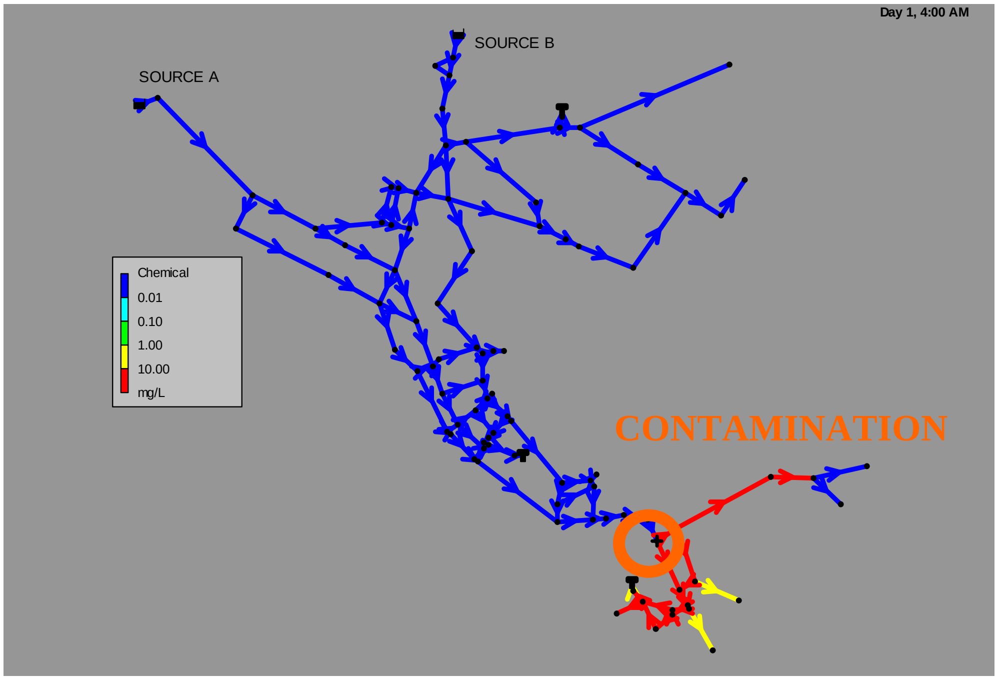

Figure 2. A hypothetical water distribution system experiencing limited dispersal of high contaminant concentrations (modeled using EPANET in Glascoe, 2004).

3.5.2 Distribution System Response

When a sensor signals a change in water conditions, a realistic response protocol needs to be in place. The most basic choices are (1) to shut down the system, (2) to divert/isolate the water, or (3) to open the system (ASCE, 2004; ILSI, 1999; and Kiwa, 2004). Distribution systems are designed for continuous flow and are not prepared for a total system shutdown that could have an extremely detrimental effect on the infrastructure. As modern distribution systems have numerous interconnected flow paths, the diversion or isolation of potentially contaminated water requires the development of a rapidly controllable system over the entire distribution network. Such modifications necessary to a distribution system could involve significant and expensive changes to the infrastructure including re-routing of pipe networks and installation of diversion storage tanks or reservoirs. Alternatively, water within a distribution system can be flushed-out by opening fire hydrants. This option, however, releases contaminated water from a closed system into the open with the possible unintended consequence of further exposing the populace to contamination. Depending on the water contaminant, flushing the distribution system into the environment could possibly cause even greater harm to the exposed population. With any of the three basic response options discussed above, valves need to be locatable and completely closeable. Thus, design of a water distribution sensor system must include the expected utility emergency response that can be used to optimize the locations of new valves and sensors.

4 Sensor Specifications and Selection Requirements

Water monitoring sensors tend to fit into a set of three 'tiers' of varying speed-of-response and sensor-complexity (Figure 3). Tier 1 sensors are typically a rapid response technology that continuously monitors key water quality parameters or specific contaminants to identify sudden changes in water chemistry within the pipeline; Tier 2 sensors have a slower response, are chemical-specific, and will often be initiated by a Tier 1 sensor response; Tier 3 'sensors' are slow but precise off-site evaluations that are usually associated with forensic analysis conducted well after the contamination event has occurred. As this survey is concerned with EWS, our focus and technology list is mainly on Tier 1 and some Tier 2 sensors. We do not focus on Tier 3 sensors.

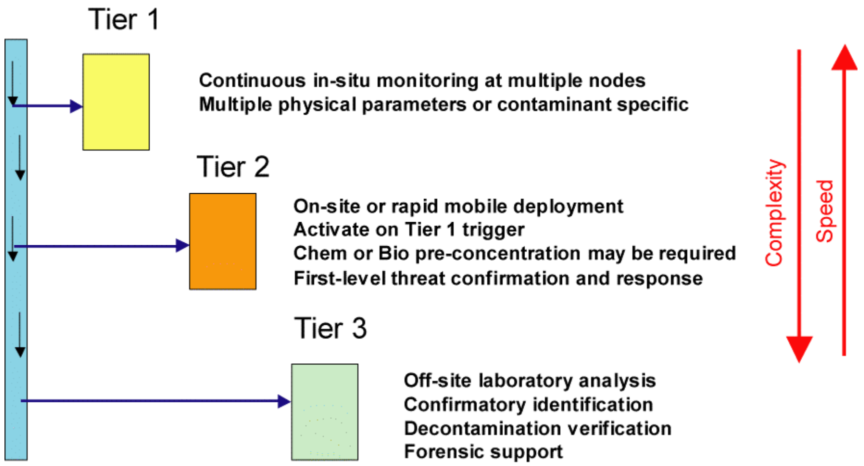

Figure 3. A multi-level monitoring strategy consists of three tiers of technology of varying speed and complexity.

4.1 Rationale for Sensor Criteria

There are many different types of both water-quality and contaminant sensors available. In the appendix of this document a compiled database of commercially available water monitoring sensors collected primarily from surveys performed by several organizations, (ASCE, AWWA, EPA, DOD, KIWA, and Sandia National Laboratories) is presented based on our review of the current market. Table 3 lists the important operating, economic, and performance sensor parameters that have been identified from our review of the technologies. These listed parameters listed are employed to help catalog sensor technologies for our database, are useful to illustrate important differences between sensors, and can assist in the down selection of sensors for water utility use. Appendix I of this document is an Excel spreadsheet database of commercially available sensors and their specifications. The database parameters are presented in a slightly different form than the Table 3 parameters due to vendor data availability and the need to develop a sorting/searching capability in the spreadsheet. Table 3 and the Appendix are also the basis for establishing an acquisition-criteria which ultimately are developed to assist the water utilities in their decision making process when selecting a sensor technology (see the example in Appendix III).

Our sensor recommendations result from the realities of water-utility needs and the available sensor technology. The list of potential drinking water system contaminants is long, even if only various acute biological and chemical agents are considered. Commercial sensor technology must be able to cover this list of potential threat agents if reliable detect-to-warn security is to be achieved. Our recommendations for current systems would implement sensors that evaluate numerous overall water quality parameters. Detection of changes in the monitored water quality parameters would indicate contaminant infiltration into the distribution system. This approach has been supported by discussions with representatives of water utilities who can also utilize such sensors for optimization of water quality performance under regular conditions.

4.2 Sensor Parameters

Sensor parameters are the important categorizing attributes of a sensor and are useful for assisting in crucial decisions for selecting sensors for an intended application. The sensor parameters that cover our sensor selection criteria are based (1) on discussions with water utility representatives, and sensor technology representatives; and (2) on water sensor criteria previously established by other organizations (AWWA, 2005; KIWA, 2004; ASCE, 2004; AWWA, 2002). Detailed below are descriptions of each of the thirteen Table 3 sensor acquisition parameters.

4.2.1 C1. Availability of Performance Test Data

Testing programs that establish instrument performance in the areas of accuracy and precision, detection level, calibration stability, maintenance and operation issues, and ease of operation are viewed as highly desirable in making technology choices. The EPA Environmental Technology Verification (ETV) program provides test data from voluntary commercial vendors, while the more independent EPA's Technology Testing and Evaluation Program (TTEP) provides reliable performance information from an objective source.

Table 3. Sensor acquisition parameters.

Sensor Specification	**Range**
C1. Availability of Performance Test Data	(high, medium, low)
C2. Calibration stability	(fine, moderate, coarse)
C3. Capability for Multiple-use	(single, few, many)
C4. Data Interpretation/Management Software	(low, medium, high)
C5. Detection Range/Sensivity	(low, medium, high)
C6. Installation Logistics	(complex, routine, minimal)
C7. Maintenance & Operations – Labor	Low, Moderate, High
C8. Maintenance & Operations – Materials	Low, Moderate, High
C9. Rate of False +/-	(low, moderate, high)
C10. Response Time	(slow, moderate, fast)
C11. Sampling Configuration or Architecture	(in-line, slip-stream, grab-sample) (continuous vs periodic cycling)
C12. Technology Cost	($100 to $20000)
C13. Technology Group	(See description below)

4.2.2 C2. Calibration Stability

The sensitivity and range of detection for each sensor is important for ensuring that the sensor is appropriate for meeting specific EWS needs. Sensors must be sensitive enough to detect contaminant levels at the thresholds where acute exposure is a concern, and must also respond if contaminant concentrations are extremely high (note that some sensors will provide no signal when the concentrations exceed the normal operating range). The sensors must also be precise enough to distinguish the difference between normal fluctuations and distribution system contamination. Most sensors for direct distribution system monitoring have numerous small and sensitive components that are affected by environmental conditions. Few sensors have a long-term record of performance in distribution systems. Durability and the ability to handle fluctuating environmental conditions over time are unknown for many sensors. Environmental conditions, such as temperature and pH, can affect factors such as sensor corrosion, sensitivity, and selectivity. These conditions will vary between different distribution systems or even at different locations in the same distribution system.

4.2.3 C3. Capability for Multiple-use

Some sensors are capable of detecting multiple specific contaminants or multiple non-specific aqueous conditions. Sensors that can detect multiple specific contaminants utilize technology to separate the various contaminants into distinct signals, whereas sensors that detect multiple non-specific changes in water conditions utilize multiple sensors configured into a single installation platform. Either of these multiple-use sensors provides more information at each installation point than a sensor that detects only one water quality parameter. Typically, a utility has a strong interest in using multiple sensors to assess overall water quality as well as to detect a contamination event. To that end, information or experience with the candidate sensors in a multiple-use environment is an important consideration in the selection process.

4.2.4 C4. Data Management/Interpretation Software

This parametric refers to the availability of software algorithms to process the multivariate data coming from the sensor in such a way that significant baseline excursion events caused by contamination can be reliably detected. Additional considerations include determining whether the software can be obtained from a different vendor than the sensor vendor and whether the software can accommodate additional sensor data and “non-standard” data such as UV absorbance or total dissolved organic carbon. Other considerations include the degree to which site-specific “learning” by the analysis system is required to enable the reliable differentiation between normal baseline shifts and actual contamination events. The degree of technical expertise required to set up and to optimize the software system for each monitoring site is an important consideration.

4.2.5 C5. Detection Range/Sensitivity

Water sensors may come in contact with a wide range of physical, chemical and biological conditions, and it is important to ensure that the range and performance of the sensors be compatible with the needs of the specific distribution-system in which they are to be placed. The sensor sensitivity and selectivity are likely to be affected as the conditions in the aqueous matrix changes. Such changes need to be well characterized and understood in order to have confidence in its utilization. For a distribution system, aqueous conditions that may affect sensor performance include seasonal temperature fluctuations and changes in source water conditions; aqueous conditions will vary for different disinfection systems. Verification of sensor performance to meet sensitivity and selectivity requirements is critical to ensuring the fidelity of an EWS system.

4.2.6 C6. Installation Logistics

Depending on the sensor and its location, sensor installation can range from technically difficult and expensive to straightforward and relatively inexpensive. The size of the instrument is of some importance to the extent that it will fit in existing shelters, and many sensors may require specialized expertise for installation and set-up. Whether or not sensors installation requires service interruption is an important consideration as well.

4.2.7 C7. Maintenance and Operation -- Labor Requirements

In addition to the purchase price of the sensor (see C12) and operational costs (see C8), sensors installed within a distribution system will require periodic maintenance with an associated cost. Some sensors require more routine maintenance than others. Depending on the availability of personnel and resources, the maintenance requirements can often be the most significant cost of a sensor. Generally speaking, water utility operation and maintenance duties are performed by technicians with limited advanced training in analytical equipment, electronics, and/or chemistry. This greatly reduces the resources available to routinely service technically complicated instruments. Therefore, sensors that are simple to operate, troubleshoot, and maintain are preferred. Training requirements for technicians should be minimal and easily understood.

4.2.8 C8. Maintenance and Operation -- Material Requirements

In addition to the purchase price of the sensor (see C12) and labor costs (see C7), sensors installed within a distribution system will require periodic 'material' requirements with an associated cost. Typically such requirements include power consumption and data communications, but some sensors also have components that are consumed during operation and require replenishment. Similar to maintenance costs, depending on the availability of personnel and resources, the operational requirements can often be the most significant cost of a sensor. Sensors requiring consumables are less desirable, but may be reasonable if the consumable is inexpensive and replenishment can be part of the regular maintenance cycle. Additionally, the life expectancy of a sensor should be considered. Life expectancy of a sensor represents the time that a sensor can reasonably be expected to operate under normal conditions. The sensor may be able to perform beyond this time, but the required operation and maintenance costs may justify sensor replacement at the end of its life expectancy. Depending on the initial sensor cost, longer life expectancies may mean lower replacement costs over time. The tradeoff between sensor cost and life expectancy should be evaluated in the context of each specific utility's needs. While it is impossible to accurately assess the true costs of operations for each sensor in each distribution configuration, we have attempted to group operation costs using any guide from the manufacturer's information and our best judgment into the following groups: inexpensive ($0 to $100 per location per year), moderate ($100 to $1000 per location per year), and expensive (over $1000 per location per year). These costs should be recalculated for each distribution system assessment, as they may be unreliable for any specific application.

4.2.9 C8. Monitored parameters

Depending on the sensor technology, the characteristic of the distribution water that is being monitored can vary considerably from high contaminant specificity to completely non-specific. This sensor specification indicates the type of parameter the sensor is designed to detect.

4.2.10 C9. Rate of false positives/negatives

A false positive is a sensor's signal that is interpreted as a change in conditions when, in fact, no such changes have occurred. A false negative is when a sensor does not signal when conditions have, in fact, changed. There are numerous reasons for such failures including electronic issues, matrix effects, sensor misplacement or mis-installation, and simple sensor malfunction. For an EWS, false negatives are to be minimized to the greatest possible extent. False positives must be low enough that a sensor alarm is not ignored and continues to receive an appropriate verification/emergency response. Note that most of the sensor manufacturers do not advertise the rate of false positives or false negatives.

4.2.11 C10. Response time

The sensor response time is critical when evaluating its applicability for an EWS. The response time is determined by the time from sensor exposure to sensor signal generation. This specification as reported in the database only relates to the sensor itself. The response time of the sensor differs from the response time of the EWS. The EWS response time is roughly the cumulative time required for (1) the information from the sensor to be communicated to central processing, (2) the information from the sensor to be compared to regular distribution system fluctuations, and (3) the information from the sensor to be integrated into an EWS. This EWS response time will be the expected additional time required after an event to begin a response to the emergency.

4.2.12 C11. Sampling Configuration and Architecture

We consider consider three separate sensor architectures: (1) “in-line” sensors are situated directly into the pipeline and, subsequently cannot have a waste-stream; (2) “slip-stream” sensors measure water continuously diverted from the bulk flow; and (3) “grab sample” sensors measure water collected periodically from the distribution system. In-line and in-pipe sensors are preferred for their simplicity for analysis and sampling especially in remote locations. Slipstream sensors take water from the main water flow and usually produce a waste stream that must be diverted to a sewer-line. This diversion can require significant changes to the distribution system structure (ASCE, 2004). Grab sample analysis requires an actual sample to be taken from the water stream and transported to a field instrument. This is typically more labor intensive; and therefore, sample frequency is limited. Instruments requiring a grab sample can not be monitored remotely and thus were included as Tier 2 products in the database. Open system sensors are often developed for other usages, such as groundwater monitoring and must be converted for pipeline distribution usage.

Sensor sampling rates are an important consideration. Sensors that are not continuous monitors, often sample with a certain fixed frequency. Typical sample frequencies are less than a couple of minutes; however, longer frequencies may be preferred in specific circumstances (ASCE, 2004). The sampling cycle can either represent a discrete sample taken at specific intervals or a composite sample. The discrete sample would consist of water present only at the time of sampling/analysis. The composite sample would consist of all of the water present since the last sample/analysis. Some sensors automatically take a grab-sample when there is a significant change in conditions. This allows for Tier 2 or Tier 3 analysis to occur on the suspect water that caused the significant change in the initial sensor’s response. This is especially useful for transient water conditions where the suspect water could be downstream of the initial sensor by the time a manual sample could be taken at that location.

4.2.13 C12. Technology Cost

Sensor cost is an important consideration for water utilities with limited budgets for sensor acquisition. Sensor costs affect sensor density, in that the lower the cost of the sensor, the more sensors can be purchased. Although some sensors can be expensive, it should be noted that the individual sensor cost is often negligible compared to installation and maintenance costs over the lifetime of the sensor (see C7 and C8). In the database, we state only the listed price of the sensor; however, in assessing the real cost of sensor implementation, installation and maintenance costs (see C6, C7 and C8) of the individual distribution system need to be included in the total economic assessment.

4.2.14 C13. Technology Group

Numerous analytical approaches can be used to characterize changes in water distribution systems. In order to compare similar technological approaches in the cost and performance criteria, we have grouped sensors into basic analytical technology groups. While some sensors easily fit into certain defined groups, others do not. Where unique approaches are implemented, there will only be one item within a group. For clarification, “Electrochemical” is one of the Technology Groups listed in the database. Numerous detection methods are based on electrochemical principles, and the particular method used by a given sensor for a given parameter is detailed in the “Specific Technology” subcategory. In the case of multi-parameter sensors, Multi Parameter is listed as the Technology Group. Although there may be some similarity between different sensor technologies, distinctions are made with regard to specific technologies. This information is included to assist the understanding of specific sensor differences in the cost and performance criteria within a given Technology Group. For example, within the “Electrochemical” Technology Group, conductivity can be monitored using an “Inductive Cell” or a “Toroidal” measurement. Typically, the nomenclature used in the “Specific Technology” subcategory do not change when a Multi Parameter instrument is included as the particular technology could be matched up with individual parameters.

4.3 Sensor Selection Requirements

As part of the “Task 1” component of this Department of Homeland Security funded OTD project, we received guidance from a project Advisory Board. Table 4 lists the 69 specific guidance points provided by the Task 1 team from the Water Security Demonstration Advisory Board concerning sensor selection criteria on January 10, 2005.

Table 4. Requirements for water sensing technologies as devised by the Water Security Demonstration Advisory Board – Jan. 10, 2005.

Issue	Requirement
General	Technology requirements should primarily be **stakeholder driven** (comments from L Brooks, DHS)
	Focus on **chemical** contamination instead of specific human pathogens? Biological contamination (I thought we were going to entertain surrogate indicators to biologicals such as particles, turbidity, etc.) – we are in funded as part of the Chemical Portfolio (comments from L Brooks, DHS)
	Meet needs of **largest population possible** - cover largest municipalities (comments from L Brooks, DHS). This statement seems to be in conflict with the first sentence above. If we focus on the largest systems, it’s likely the solutions will not meet the needs of smaller utilities…but the solutions may be scalable.

Dual-use	Dual use – technology should **span other programs and meet other needs Dual-use** (comments from L Brooks, DHS)
	Multi-use sensors – can the same sensor be placed in multiple areas vs different sensors placed at many locations (installation, operation, maintenance issues).
	Want **water quality baselines**. Monitoring technologies should be used to establish water quality baselines from both the source water and distribution systems of a particular system. Sensors monitor for parameters that could be considered “indicators” and baselines must be established before contamination events may be recognized. (comments from C Schreppel, AWWA/MVWA)
	Consider **long term applications and emerging technologies** (BioWatch technologies and other commercially available air monitoring instrumentation could be used if water could be aerosolized within a safe enclosed container). This would enhance the sensitivity of sensors. (comments from Y Mikol, NYCDEP)
	Detection of **low-level environmental contaminants (**pharmaceuticals, dairy and agriculture run-off issues) (comments from D Requa, DSRSD)
	Real-time online – sample every 15-20 even 60 minutes or so (comments from Y Mikol, NYCDEP)
	Dual use - **accidental and deliberate contamination events** detected (comments from Y Mikol, NYCDEP) Same comment as #4. I will add that testing should include some common accidental contaminants such as gasoline or diesel fuel and a voc (tetrachloroethylene?) Sensor that will detect a number of contaminants (rather than sensor specific to only one chemical/substance). Alarm must trigger grab sample and notification (text message). (comments from Y Mikol, NYCDEP)
	A **flagging system** based upon data received from sensors: send different alarms/text messages for a spike and for a persistent condition above threshold (best situation is the ability to log on network and view the data from that instruments and other related monitoring instrumentation on the network)

Characteristics related to data output	Characteristics of select technology as related to data output. – (comments from P Biedrzycki, Milwaukee) a. High specificity/sensitivity (low false positive rate and low threshold for detection) b. Robust, precise and reliable c. Easily interpretable data – visual and easily understood, non-ambiguous d. Sustainable (low maintenance and operational costs long-term). e. Rapid/continuous as well as “near” real time f. Easily integrated into existing systems and not stand-alone system. g. Can be used by utility for routine monitoring and water quality assurance. h. “Low tech” vs. “rocket science” i. Security issues (tamper-proof?)
	Ability to interpret data – what does the data mean? Important to establish a data inference engine that can accurately monitor the severity of a detected incursion, estimate the potential outcome, and selectively alert and present the information to authorized users. (comments from C Schreppel, AWWA/MVWA)
	Data robustness from (un)published reports on priority contaminants
Technology - basics	Consider daily operations – maintenance, robustness, ease of operation Consider long term deployment issues Consider cost included in installation, operation, and maintenance (routine calibration)
	Bear in mind that the technology has to be **assimilated within a utility’s culture** for doing business, the operator’s level of understanding of water quality – (comments from P Parekh, LADWP) j. Simplicity of instrument k. Operational flexibility – instrument should have an operational value. l. Maintenance should be within current expectations of time and materials. m. Union can have issues with new job requirements (use an exiting instrument or one that is similar and adapt it to different conditions is preferable to a new instrument)

	Connection with how utilities currently manage water quality system events would provide credibility to efforts. ((comments from P Parekh, LADWP)
	Connection with real-world problems that also have public health consequence (coliform, spike in turbidity, etc) would be of value. ((comments from P Parekh, LADWP)
	Ability to **integrate technologies** into existing systems. Monitoring technologies and the mechanisms to interpret the data should have the ability to be integrated into existing systems used by water systems (e.g. SCADA and GIS based technologies). (comments from C Schreppel, AWWA/MVWA); Integration with other sensors – will the sensor integrate with existing sensors/monitoring devices? (comments from Y Mikol, NYCDEP)
	Current **education level of staff**. User friendly for operator level personnel, low maintenance. (comments from C Schreppel, AWWA/MVWA); Level of expertise required to use the instrument - is it compatible with experience/education of staff (comments from Y Mikol, NYCDEP)
	Maintenance requirements, specifically calibration frequency (daily weekly by opposition to fish monitoring that can run unattended for 3-4 weeks) (comments from Y Mikol, NYCDEP).

5 Technology Gap and Discussion

Although major efforts are currently underway by utilities to secure their water distribution systems and to protect public health, there are currently no detect-to-warn systems available, as we have envisioned in this report. This project's task was to evaluate the current status of commercially available sensors for their use in water distribution monitoring systems. In this survey, we discovered numerous promising sensor technologies that are currently in development. Promising technologies are under development that are primarily focused on rapid detection to achieve high contaminant specificity either through miniaturization of existing analytical approaches or the development of new sensors based on molecular interactions/binding to sensor surfaces (Battiston et al, 2001; Emili and Cagney, 2000; Hergenrother et al, 2000; Lang et al, 1999; Marshall and Hodgson, 1998). These new technological developments may ultimately provide some of the sensors required for a proper detect-to-warn capability.

Currently the list of possible water contaminants is too long for any sensor array to be practical for a detect-to-warn system in the foreseeable future. In order to assist the development of sensors for detect-to-warn systems, a complete list of the acute contaminants where specificity is sought should be compiled based on realistic risk assessment scenarios.

In addition to the development of better, faster, and cheaper sensor technology to attain proper detect-to-warn systems, significant thought and financial investment must incorporate the necessary developments into new distribution systems, as well as the reengineering of existing systems. Such changes put an increased burden on the water distributor for support of homeland security needs. An EWS requires more than just the instrumentation of the water distribution system, it also requires that appropriate action be taken to minimize the loss of life during a contamination event. The decisions for appropriate response actions will be different depending on the configuration of the distribution system, and will need to have appropriate governmental and professional coordination/guidance to develop a consistent methodology for ensuring the protection of the public.

6 Summary and Conclusions

The security of our nation's water supply has been a concern both before and after the events of September 11, 2001. Several notable studies have investigated water distribution system security issues including studies by EPA, ILSI, AWWA, ASCE, and Kiwa. Several important issues have been identified through these efforts:

- Given the current state of sensor technology, surrogate water quality parameters are the best approach for distribution system contamination event monitoring. In our sensor survey, we found a limited number of 'Tier 1' sensors that are commercially available. These few available in-line sensors generally measure surrogate parameters rather than specific contaminants. The need for additional monitoring to identify the specific nature of the contaminant is implied in this approach.
- A clear understanding of the normal variability of baseline water data is needed to accurately interpret surrogate water quality data in a contamination event. Several testing programs are developing methods to address this issue including EPA ETV, EPA TTEP, and ECBC.
- Distribution system contaminant transport modeling is an important component in the design of an EWS. Contaminant transport and hydraulic computer models such as EPANET are available and are being used in programs such as EPA's TEVA effort to assist in sensor placement, to determine possible contaminant transport pathways, and to assist in emergency response and forensic analysis.
- The objective of an EWS in terms of detect-to-warn and detect-to-treat needs to be more clearly defined.
- Emergency response protocols and procedures needed to react to contaminated water distribution systems require further development.
- There exists a technology gap between current sensor technology and needed sensor technology for EWS.
- To be deployed by utilities, sensors must generally be inexpensive, easy to maintain, reliable, and have a low rate of false positives and false negatives, among other requirements.
- The particular needs of water utilities are site specific and will vary, within certain parametric bounds, from distribution system to distribution system.

In developing solutions to these security issues, the needs and resources of the water utilities is of fundamental importance. For any solution to be helpful, it must be constructed within the water utilities' available resources.

7 Appendix I: Compiled Database of Sensors

(see attached document "Compiled Data Base of Water Sensors: Instrument Descriptions" by Johnson et al., 2005)

8 Appendix II: Programmatic Gaps and Proposed Resolutions

The Department of Homeland Security (DHS) has tasked a multi-laboratory team to evaluate current and future needs to protect the nation's water distribution infrastructure by supporting an objective evaluation of current and new technologies. This effort has been funded as part of an Operational Technology Demonstration (OTD). Lawrence Livermore National Laboratory and Sandia National Laboratories were tasked with the development of a technology acquisition process, referred to as the Task 2 effort. Lawrence Livermore National Laboratory and Sandia National Laboratories have met the requirements of this task with the following two deliverables: (1) *Sensor Acquisition for*

Water Utilities: A Survey and Technology List, UCRL-TR-210488/SAND2005-2671P and (2) *Compiled Database of Water Sensors*, UCRL-MI-211877 submitted April 29, 2005 and May 2, 2005 respectively. This appendix serves to identify potential areas for follow on effort and funding that are a natural progression of the Task 2 work.

In Task 2's review and compilation of the current state of water sensor technology and consultation with various members of the OTD Task 1 Advisory Board, we have identified two key areas that would benefit from additional funding and effort: (1) the development of a more detailed methodology for selecting sensors for various specific applications, and (2) the expansion of the Task 2 sensor database into an advanced database.

8.1 Toward a More Detailed Sensor Down Selection Criteria

The Task 2 report, *Sensor Acquisition for Water Utilities: A Survey and Technology List*, UCRL-TR-210488/SAND2005-2671P, identifies sensor acquisition parameters in Table 3 and in Section 4.2. Review of previous studies of Early Warning Systems (EWS), sensor technology, and discussions with water utilities demonstrate that no single sensor can meet all of the various water distribution systems' needs (ASCE, 2004; AWWA, 2005). While it would be convenient to apply a one-size-fits-all down selection process for all utilities, it would be inappropriate, as the selection of contaminant sensors is a complex problem that requires extensive and detailed analysis (AWWA, 2005; Kiwa, 2004).

It is desirable to have a down selection methodology that would be useful for specific classes of water distributions systems. Categorizing water utilities into classes by, for example, the age or the size of the water distribution system, or by the financial resources available to the water utility, could assist in focusing the generalized sensor down selection process for specific utilities. Such a refined down selection capability could involve a thorough system analysis including, but not limited to, water distribution system studies such as the TEVA effort to reduce parametric uncertainty in complex water distribution systems. This tool may include multiattribute utility theory to evaluate alternatives for complicated problems with multiple objectives (e.g., Dyer et al., 1998), or might involve a stochastic approach to guide optimal sensor placement within distribution systems (e.g., Murray, 2004; Johannesson et al., 2004). Such methodologies have been successfully applied to problems including the disposition of surplus weapons grade plutonium, the siting of an electricity generation facility (Dyer et al., 1998), improved predictions of contaminant transport through geologic material (Aines et al., 2002), and improved sensor and source analysis for atmospheric dispersion problems (Johannesson et al, 2004). Additional fidelity could include the economic considerations for both (1) employing current technologies in an EWS role for water distribution systems and (2) developing emerging sensor technologies specifically for water distribution system use.

While the authors of the Task 2 documents refer to sensor-placement issues, alert management, and emergency response, a few more references and discussion points may be relevant here. Some of the emergency response capabilities that the Department of Homeland Security is investing in should be considered -- for instance the recent

TOPOFF3[3] interagency exercise for emergency response to atmospheric release may be relevant to water distribution EWS emergency response issues.

8.2 Toward an Expanded Sensor Database

The sensor database, *Compiled Database of Water Sensors*, UCRL-MI-211877, was necessarily submitted as a Microsoft Excel spreadsheet[4] given the time and budget constraints of the OTD project. While the database is comprehensive in both number of sensors represented with relevant attributes for selection criteria and is searchable on several different levels using the sensor parameters, this tool could be made more powerful by incorporating the list into an advanced and dynamic database such as Microsoft Access. To maintain its usefulness, the database would need to be a "living" document with a point of contact to add new sensor information as it became available. Additionally, a communication path, such as an internal web site, should be established that would facilitate sensor information going back and forth between water utilities, vendors, test programs, and the database point of contact.

An alternative to developing a more advanced database is to incorporate the sensor database information into EPA's comprehensive water sensor database currently being developed which would allow the DHS effort to add benefit to an existing program. The upcoming EPA database is likely to be the central source of sensor data and will be a resource to continue the dataflow with water utilities, vendors, and test programs.

An inherent weakness on the part of the sensor database is the dependency on information from private vendors. The gathering of current, relevant, and objective information is a difficult task. To address this problem, comprehensive involuntary testing programs of sensors such as the EPA's Technology Testing and Evaluation Program (TTEP)[5] can provide reliable performance information from an objective source.

9 Appendix III: A Hypothetical Technology Down-Selection Process

In this appendix we present an example of how a down selection of candidate sensor technologies could be carried out using utility-specific selection parameters for a hypothetical utility. In the technology down selection process it is important to note that it is unlikely that a common set of selection criteria will represent the needs of each domestic water utility industry. Each utility will possess specific needs and requirements that will be tempered by such factors as the size of the utility, the extent to which monitoring is already done, the utility's capital improvements budget, the locally perceived contamination threat spectrum, as well as other factors. Consequently, the following exercise is intended to be exemplary and not proscriptive. Furthermore, it bears emphasis that the ability of the various candidate technologies to meet the outlined selection criteria cannot, in most cases, be fully determined from the instrument specification sheets provided by the instrument vendors. In many cases, details required for a completely objective down selection process are not provided. Often the type of information desired is only available through a testing program such as being advocated

---

[3] http://www.ojp.usdoj.gov/odp/exercises.htm#topoff3

[4] Note there is companion text in the document, *Compiled Database of Water Sensors: Instrument Descriptions*, UCRL-MI-211877, providing a summary of each of the sensors in the database.

[5] http://www.epa.gov/ordnhsrc/tte.htm

in the OTD Project. In light of these shortcomings it is apparent that expert judgment is required in many cases to move the entire process forward. As the various EPA-sponsored testing programs such as the Environmental Technology Verification (ETV) program, the Advanced Monitoring Systems Center, and the Technology Testing and Evaluation Program (TTEP) continue to carry out testing, these information gaps may in fact be filled, thereby making the technology selection process less subjective for the acquiring utility.

9.1 Hypothetical Monitoring Objective

In this example, we assume that a hypothetical utility is interested in a moderate expansion of their existing monitoring capabilities for a contamination event with a specific interest in monitoring within their distribution system. We further assume that the hypothetical utility is interested in the development of a “detect-to-treat” application in contrast to a “detect-to-warn” application. A detect-to-treat application places less emphasis on the timeliness or the specificity of response since the assumption is made that additional instrumentation or diagnostics will be required to more fully ascertain the nature and extent of the contamination. A detect-to-warn application, on the other hand, places the highest constraints on such a monitoring system since time is of the essence and false positive and negative rates must necessarily be low since decisions to warn the consumer may be based on this single tier of sensors alone. The utility is interested in the detection of both chemical and biological contamination; however, given our common understanding of the present commercially available sensor systems for the detection of biological contaminants, there is an implicit understanding that chemical contamination is likely to be better addressed than biological contamination through the chosen technology.

Table A1. Parameters for Technology Down-Selection

Parameter	Utility Ranking
C1. Availability of Performance Test Data	High Priority
C2. Calibration Stability	Low Priority
C3. Capability for Multiple-use	High Priority
C4. Data Interpretation/Management Software	High Priority
C5. Detection Range/Sensitivity	Medium Priority
C6. Installation Logistics	Medium Priority
C7. Maintenance and Operation – Labor	High Priority
C8. Maintenance and Operation – Materials	Low Priority
C9. Rate of False +/-	Low Priority
C10. Response Time	Low Priority
C11. Sampling Configuration	High Priority
C12. Technology Cost	Medium Priority
C13. Technology Group – Multi-parameter	High Priority

9.2 Hypothetical Utility Selection Criteria

A list of sensor performance parameters, such as might be developed at a water utility for the selection of a sensor technology in order to expand the monitoring capability within the distribution system, are derived from Table 3 in the main text. The utility then ranks the parameters C1 through C13 as being of "high", "mid", or "low" priority (see Table A1). Each of these parameters and their associated ranking are further discussed in the context of the utility in the following paragraphs.

9.2.1 C1. Availability of Performance Test Data

This category holds a high priority for the utility since having knowledge of the long-term reliability of the sensors, via third-party testing, is judged to be an important piece of information when final sensor selections are to be made. Testing programs that establish instrument performance in the areas of accuracy and precision, detection level, calibration stability, maintenance and operation issues, and ease of operation are viewed as highly desirable in making technology choices.

9.2.2 C2. Calibration Stability

Calibration stability is of lower importance since the measured *change* in the baseline is of primary interest in this case and there is less interest in the absolute value of any of the measured parameters. The expectation is that software algorithms associated with the multi-parameter sensors will be able to differentiate between the baseline perturbations caused by sensor drift or normal water quality changes and those caused by an actual contamination event.

9.2.3 C3. Capability for Multiple-use

The hypothetical utility has a strong interest in using these sensors to assess overall water quality for the consumer as well as offering additional detection capabilities for a contamination event. To that end, information or experience with the candidate sensors in a dual-use environment will be an important consideration in the selection process.

9.2.4 C4. Data Management/Interpretation Software

This high-priority category refers to the availability of software algorithms to process the multivariate data coming from the multi-parameter sensor in such a way that significant baseline excursion events caused by contamination can be reliably detected. This holds a very high priority in light of the fact that the utility is specifically interested in a multi-parameter sensor. Additional considerations include a determination of whether the software can be obtained from a vendor different than the supplier of the multi-parameter sensor and whether the software in can accommodate "non-standard" data inputs (such as UV absorbance or total dissolved organic carbon). Other considerations include the degree to which site-specific "learning" by the analysis system is required to enable the reliable differentiation between normal baseline shifts and actual contamination events, as well as the degree of technical expertise to set up and optimize the system for each monitoring site.

9.2.5 C5. Detection Range/Sensitivity

While this parameter is certainly of interest to our hypothetical utility, its importance is deemed of intermediate value. This is because the multi-parameter approach is intended to provide a "state-change" indication by examining trends in the physical parameter baseline. Given that the water quality baseline is constantly changing, the sensitivity of the sensors becomes less important since the sensor system is essentially looking for gross changes within the system baseline in order to flag a possible contamination event.

9.2.6 C6. Installation Logistics

This category holds an intermediate priority for our hypothetical utility since, as noted previously, installation locations for the sensors have already been determined such that waste stream access and power/shelter are available. The size of the instrument is of some importance to the extent that it will fit in existing shelters.

9.2.7 C7. Maintenance and Operation – Labor

This category also holds a high priority since, based on the hypothetical utility's past experiences, labor costs required for long term maintenance and operation of the sensor systems will be the largest expense associated with the total life-cycle cost. The hypothetical utility's expectations are that each multi-parameter sensor unit will require no more than one hour of on-site technician service time per month. The utility has an interest in expanding their autonomous sensor network within the distribution system. They are specifically interested in those sensors that can operate unattended for extended periods of time. Consequently, this particular category holds a high priority. Further implied is the feature of minimal personnel intervention during normal operation and a requirement that sensor output data be integrated into an existing utility SCADA system.

9.2.8 C8. Maintenance and Operation – Materials

Material costs associated with sensor upkeep do not hold a high priority with our hypothetical utility. Based on the previous observation, the utility understands that most of the maintenance and operation costs will fall into the labor category and that sensor service and replacement costs will be relatively insignificant.

9.2.9 C9. Rate of false positives/negatives.

While the rate of false positives/negatives is an important consideration, especially for detect-to-warn systems, the priority is rated as low for our hypothetical utility. This is because there is currently not enough information to define false +/- rates at this time for the candidate systems, largely due to a lack of third-party testing (see C1).

9.2.10 C10. Response Time

Since the application is detect-to-treat, response time for our hypothetical utility is less of a concern than it would for a detect-to-warn system. Response time on the order of 15 minutes is likely to be adequate for the intended application.

9.2.11 C11. Sampling Configuration

Sampling configuration refers to the nature of the sensor installation and can be either in-pipe or external to the pipe for an autonomous sampler. This holds a high priority for our example utility since only in-pipe or small-footprint external-to-pipe configurations will meet the utility's stringent installation requirements. Installation will occur at pre-determined locations with sewer connections so that a waste stream from the sensor will not pose any difficulties.

9.2.12 C12. Technology Cost

The cost of the sensor technology holds an intermediate priority with our hypothetical utility and is based upon the fact that, in the utility's experience, maintenance and operation costs over the lifetime of the sensor system will dominate the total system cost. Acquisition costs in the range of $10,000 to $30,000 per sensor unit are not regarded as burdensome.

9.2.13 C13. Technology Group

The technology group is another high-priority selection parameter for our example utility, and in this case the utility is interested in the *multi-parameter* sensor category. This category holds a high priority for the hypothetical utility, since they are aware that there is empirical evidence that simultaneous measurements of several physical parameters at the same location offers the potential to detect contamination events outside the normally observed physical parameter baseline excursions within the distribution system. The combination of multiple sensors into one electronics package is appealing from the perspective of system cost, compactness, and overall efficiency. Furthermore, the utility is interested in proven sensor technology, and, thus, the conventional sensor systems for physical parameters such as pH, conductivity, turbidity and residual chlorine are considered favorable candidates.

9.3 Hypothetical Utility Candidate Technologies

With the previous selection parametric criteria in hand, we now review the list of candidate technologies for the hypothetical utility, and perform a sensor down selection to a subset of technology candidates. In the following paragraphs we consider the available technologies within the database in light of the selection criteria already outlined. A technology down selection based a hypothetical utility's interest in the multi-parameter probe category only (see Section 9.3.13) is given in Table A2.

9.3.1 Candidates and C1: Availability of Performance Test Data

Of the subset of multi-parameter probes listed in Table A2, only the YSI Model 6600 Extended Deployment Probe (6000 series in database) has undergone rigorous third-party testing as a part of the US EPA ETV Program. Other probes from both Hach and YSI are in various EPA Cooperative Research and Development Agreement (CRADA) test programs; however data from these programs may be proprietary and may not be accessible to the public. Limited testing of the WST Censar Multi-parameter probe has also been carried out by the EPA and selected utilities.

9.3.2 Candidates and C2: Calibration Stability

Various claims are made by vendors regarding calibration methodology and stability. Since the sensors are primarily intended for use as a baseline trending indicator, absolute calibration stability does not hold a high priority. Furthermore, information on calibration stability and required frequency is best obtained through third-party performance testing.

9.3.3 Candidates and C3: Capability for Multiple-use

All of the probes listed in Table A2 measure physical parameters that are of interest in general water quality measurements for the distribution systems, and, thus, are applicable for a dual use function. Several of the probes (Primayer PrimeCense Color and Turbidity and WST Censar CT Sense) measure only temperature, turbidity and color, parameters that are judged to be too restrictive for a broad contamination detection capability. Consequently they are not included in the final candidate list to be discussed later.

9.3.4 Candidates and C4: Data Interpretation/Management Software

All of the probes listed in Table A2 have data loggers that can be purchased as an accessory to the probe unit. All data loggers can be interfaced to a utility SCADA system as well. With the exception of the Hach Pipesonde, these data loggers simply record the various parameters (e.g. temperature, turbidity, residual chlorine) and store them for time series plotting by an operator. No multivariate analysis of the various sensor readings can be carried out with these basic data loggers. Further data manipulation for increased ability to elucidate a possible contamination event would require additional software and computer facilities, possibly within the utility SCADA system. The Hach product line is an exception in this case. Hach offers an accessory product to the Pipesonde called the “Event Monitor” which includes a processor, display graphics, and proprietary statistical algorithms that further manipulate the multivariate data stream for increased ability to detect a contamination event.

9.3.5 Candidates and C5: Detection Range/Sensitivity

In general, the detection range and sensitivity of the various parameters are comparable as most manufacturers are using a similar technology base for their sensors. Previous experience has shown that the following parameters hold the most importance for in-pipe contamination detection: temperature, pH, conductivity, residual chlorine, dissolved oxygen and turbidity. Measurement technologies for these parameters are relatively well proven. An exception in this case is the chip-based sensor offered by Primayer and WST. This is a relatively new technology that has a somewhat different technical foundation than most of the other probe technologies listed in the database. Concentration ranges reportedly measured by these chip-based sensors are similar to the conventional sensors. Total organic carbon (TOC) has also been shown to be a useful parameter for the detection of contamination; however, none of the vendors offer TOC analysis in a probe format. The TOC measurement capability is available in panel-mount configurations only.

9.3.6 Candidates and C6: Installation Logistics

All of the probes listed in Table A2 are in-pipe probes and require a similar penetration of the pipe in order to carry out the installation. Thus further down selection is not warranted based on this criterion.

9.3.7 Candidates and C7: Maintenance and Operation – Labor & Materials

Maintenance and operation details in the product brochures are limited for the probe models shown in Table A2. Replacement sensor costs are typically less than $1000 and in all cases the required labor hours to carry out sensor change out and re-calibration are not given. In view of the limited information provided, we assume that labor and material costs for these systems are comparable based on the similarities of their configuration. Nearly all the sensors listed in the database have some degree of autonomy, so this category is not useful for further down selection.

9.3.8 Candidates and C8. M&O – Materials

This priority is rated as low by the hypothetical utility.

9.3.9 Candidates and C9. Rate of false positives/negatives.

This priority is rated as low by the hypothetical utility, see Subsection 9.2.9.

9.3.10 Candidates and C10: Response Time

All listed instruments utilize relatively fast electrochemical principles for the detection of specific analytes and thus have response times that are typically less than one minute. Their response times are generally well within the desired 3-minute response time criterion.

9.3.11 Candidates and C11: Sampling Configuration

This high-priority category serves as another major filter for the candidate sensors. A large number of the multi-parameter sensor systems listed in Table A2 are intended for open water use. Many of these are probes are intended for depth profiling of ground water monitoring wells, reservoirs, oceans and lakes and are not particularly well suited for measurements in the vicinity of a water pipe. To use them in a pipeline capacity would require additional engineering and fabrication of a water slipstream from the pipe into a measurement vessel positioned in the pipe's vicinity. The measurement vessel would enable exposure of the probe to the water slipstream flow. Such additional engineering and fabrication requirements are beyond the scope of capabilities and/or budget of the hypothetical water utility and consequently, this subset of multi-parameter probes are eliminated from consideration.

9.3.12 Candidates and C12: Technology Cost

Costs for multi-probe sensors range from about $2,000 to over $25,000; and most of the probes sell in the range of $8,000 to $15,000. As previously noted in the criteria, acquisition costs are considered to be of intermediate importance in the selection process, so costs do not form the basis for further technology down selection.

9.3.13 Candidates and C13: Technology Group – Multi-parameter

Our hypothetical utility has a specific interest in deploying multi-parameter sensor systems based on the perceived monitoring efficiencies to be gained by multiple probes serviced by a common electronics module. The database contains 16 multi-parameter systems from 10 manufacturers. The technology down-selection based on this category alone is given in Table A2.

Table A2. Manufacturers and Models of Multi-Parameter Probes

Manufacturer	Model	Max. Number of Parameters[d]
General Oceanics	Ocean Seven 316	8
Greenspan	Minilab	9
	CS	4
Hach	Pipesonde	8
	Event Monitor[a]	N/A
Hydrion BV	Hydrion 10	15
Hydrolab[b]	Datasonde 5 and 5X	16
	Minisonde 5	10
	Quanta	10
In-situ	MP Troll 9000	9
Primayer[c]	PrimeCense - Multi-parameter	6
	PrimeCense - Color and Turbidity	3
UIT	Multi-Sensor Module (MSM9)	9
WST	Censar – CT Sense	3
	Censar - Multiparameter	6
YSI	6920DW (6000 series)	6
	600DW-B (600 series)	5

Table Notes:

[a] The Hach Event Monitor is a data processing unit that is sold as an accessory to the Pipesonde. The Event Monitor is not listed in the report database.

[b] Hydrolab is a subsidiary of Hach, with shared probe technologies

[c] Primayer is a UK company and WST is a US company offering the same product line.

[d] Many of the probes can accommodate a broad range of plug-and-play sensors. See the database for a listing of all of the possible combinations.

9.4 Further Down Selection of Candidate Technologies

Following the foregoing application of the hypothetical utility’s criteria, a further down selection of candidate probes in shown in Table A3. The candidate technologies are essentially those with multi-parameter capabilities that can be installed in an in-pipe configuration.

Table A3. Multi-parameter probes best suited for a water pipe monitoring application and parameter justification of highest consideration of a hypothetical utility.

Manufacturer	Model	Rationale
YSI	6000 series	C1 (ETV tested) C11 (in-pipe config) C13 (multiparam probe)
	600 series	C1 (no test data available) C11 (in-pipe config) C13 (multiparam probe)
Hach	Pipesonde	C1 (CRADA test in progress) C11 (in-pipe config) C13 (multiparam probe)
Primayer	PrimeCense - Multi-parameter	C1 (no test data available) C11 (in-pipe config) C13 (multiparam probe)
	PrimeCense - Color and Turbidity	C1 (no test data available) C11 (in-pipe config) C13 (limited param probe)
WST	Censar – Multi-parameter	(limited test data available) C11 (in-pipe config) C13 (multiparam probe)
	Censar –CT Sense	C1 (limited test data available) C11 (in-pipe config) C13 (limited param probe)

9.5 Final Technology Candidates for a Hypothetical Utility

A further down selection of candidate probe technologies is shown in Table A4 and is based on the fact that two of the probes, the Primayer PrimeCense-Color and Turbitiy and the WST Censar-Mulit-parameter have a limited analysis capability—only measuring temperature, color and turbidity. The other probes include can measure additional physical parameters that are more directly related to potential contamination events. Thus, these two probes are eliminated in the final candidate technology list in Table A4.

9.6 Other Considerations

Based on a systematic application of the down-selection criteria described previously, the probes listed in Table A4 are best suited for the intended hypothetical utility application. Some questions remain concerning the availability of multivariate data processing software to improve contamination detection. It is quite possible that the Hach Event Monitor data processing module can be used with sensor inputs from other probe manufacturers; however, this is not known for certain. If it is in fact true, then any one of the probe vendors could be an option in combination with a statistical data processing module such as the Event Monitor. On the other hand, algorithms for statistical manipulation of the data could be developed under an independent effort and integrated into an existing utility SCADA system; however, development and testing costs could be significant if this particular pathway were chosen.

If a statistical processing system is incorporated into the multi-parameter system, an additional consideration should be an assessment of the ability of the system to incorporate additional sensor inputs. As noted previously, measurements of total organic carbon have proven useful for contamination event detection. Similarly ultraviolet probes offer similar advantages for increasing the sensitivity for contamination events. In light of these considerations, the final selection should take into consideration whether the system can be upgraded by the addition of other sensors in addition to those within the multi-parameter probe.

Table A4. Final Candidate Technologies For a Hypothetical Utility.

Manufacturer	Model	Rationale
YSI	6000 series	C1 (ETV tested) C11 (in-pipe configuration) C13 (multiparam probe)
	600 series	C1 (no test data available) C11 (in-pipe configuration) C13 (multiparam probe)
Hach	Pipesonde	C1 (CRADA test in progress) C11 (in-pipe configuration) C13 (multiparam probe)
Primayer	PrimeCense - Multi-parameter	C1 (no test data available) C11 (in-pipe configuration) C13 (multiparam probe)
WST	Censar – Multi-parameter	C1 (limited test data available) C11 (in-pipe configuration) C13 (multiparam probe)

10 References

Aines, R., Nitao, J., Newmark, R., Carle, S., Ramirez, A., Hanley, W., 2002: The Stochastic Engine Initiative: Improving Prediction of Behavior in Geologic Environments We Cannot Directly Observe. Publication, LLNL Report No. UCRL-ID-148221.

American Society of Civil Engineers. 2004. Interim Guidelines for Designing an Online Contaminant Monitoring System, First Draft.

American Water Works Association. 2005. Contamination Warning Systems for Water: An Approach for Providing Actionable Information to Decision-Makers. Roberson and Morley. AWWA, Denver, CO.

American Water Works Association Research Foundation. 2002. Online Monitoring for Drinking Water Utilities. AwwaRF, Denver, CO.

Battiston, F. M.; Ramseyer, J.-P.; Lang, H. P.; Baller, M. K.; Gerber, Ch.; Gimzewski, J. K.; Meyer, E.; Gntherodt, H.-J. 2001. A chemical sensor based on a microfabricated cantilever array with simultaneous resonance-frequency and bending readout Sens. Actuators B 77, 122.

Brosnan, T.M.(ed). 1999. Early Warning Monitoring to Detect Hazardous Events in Water Supplies. An ILSI (International Life Sciences Institute) Risk Science Institute Workshop Report. Washington, D.C.:ILSI Press.

DeYoung, T. and Gravely, A. 2002. Coordinating Efforts to Secure American Public Water Supplies. Natural Resources and Environment, Winter:146-152.

Dyer, J.S., T. Edmunds, J.C. Butler, and J. Jia, 1998: A multiattribute utility analysis of alternatives for the disposition of surplus weapons-grade plutonium, Operations Research, 46(6): 749-762.

Emili, AQ and Cagney, G. 2000. Large-scale functional analysis using peptide or protein arrays. Nat Biotechnol. Apr;18(4):393-7.

Glascoe, L. 2004. Water security and water distribution networks. LLNL Document UCRL-TR-203270, Livermore, CA.

Johannesson, G., Hanley, W., and Nitao, J. (2004): Dynamic Bayesian Models via Monte Carlo - An Introduction with Examples, LLNL Report No. UCRL-TR-207173.

Haestad Methods, Inc. WaterCAD Version 5 User’s Guide. Haestad Methods, Waterbury, CT, 2002.

Hasan, J., States, S., and Deininger, R. 2004. Safeguarding the Security of Public Water Supplies Using Early Warning System: A Brief Review. Journal of Contemporary Water Research and Education. 129: 27-33.

Hergenrother, Paul J.; Depew, Kristopher M.; and Schreiber, Stuart L. 2000. Small-Molecule Microarrays: Covalent Attachment and Screening of Alcohol-Containing Small Molecules on Glass Slides, *Journal of the American Chemical Society*; 122(32); 7849-7850.

Hickman, D.C. 1999. A Chemical And Biological warfare threat: USAF water systems at risk. The Counterproliferation Papers, Future Warfare Series No. 3, USAF Counterproliferation Center, Maxwell Air Force Base, Alabama.

Ho, C.K., Itamura, M.T., Kelley, M. and Hughes, R.C. 2001. Review of Chemical Sensors for In-Situ Monitoring of Volatile Contaminants. Sandia Report SAND2001-0643. Sandia National Laboratories, Albuquerque, NM.

Kansas Department of Health and Environment, Bureau of Water. 2003. Simplified Vulnerability Assessment Tool for Drinking Water. KDHE-BOW, Topeka, KS.

Kiwa. 2004. Early Warning Monitoring in the Drinking Water Sector, threats, impacts and detection, Final draft. KIWA N.V. Water Research, Nieuwegein, Netherlands.

Lang, H.P.; Baller, M.K.; Berger, R.; Gerber, Ch.; Gimzewski, J.K.; Battiston, F.M.; Fornaro, P.; Ramseyer, J.P.; Meyer, E. and Guntherodt, H.-J.1999. An Artificial Nose Based on a Micromechanical Cantilever Array, Analytica Chimica Acta, 393, 59.

Marshall, A. and Hodgson, J. 1998. DNA chips - an array of possibilities. Nature Biotechnology, 16(1), 27-31.

Murray, R. 2004. The Threat Ensemble Vulnerability Assessment Program for Drinking Water Distribution System Security. EPA Science Forum, June1-3, 2004.

National Research Council of the National Academies. 2003. A Review of the EPA Water Security Research and Technical Support Action Plan. National Academies Press, Washington, D.C.

Rossman, L.A. 2000. EPANET 2 Users Manual. US Environmental Protection Agency Document EPA/600/R-00/057, National Risk Management Research Laboratory, US EPA, Cincinnati, OH.

Schreppel, C.K. 2003. Distribution System Security, Setting the Alarm for an Early Warning. Opflow. 29(6).

Science Application International Corporation (SAIC). Water Pipeline Network Model, Version 2.1, May 2003.

Susquehanna River Basin Commission. 2004. Early Warning System Project, Enhancing Protection of Public Water Supplies in the Susquehanna River Basin. SRBC Information Sheet. SRBC, Harrisburg, PA.

U.S. Environmental Protection Agency. 2004. Water Security Research and Technical Support Action Plan. EPA/600/R-04/063. Washington, D.C.

Uber, J., Murray, R., and Janke, R. 2004. Use of Systems Analysis to Assess and Minimize Water Security Risks. Journal of Contemporary Water Research and Education. 129: 34-40.