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Sensor Acquisition for Water Utilities: A Survey and Technology List

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Sensor Acquisition for Water Utilities:

A Survey and Technology List

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1 Executive Summary

The early detection of the deliberate biological and chemical contamination of water distribution systems is a necessary capability for securing the nation's water supply. Current and emerging early-detection technology capabilities and shortcomings need to be identified and assessed to provide government agencies and water utilities with an

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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 primary deliverables from this Operational Technology Demonstration (OTD) are the following: (1) establishment of an advisory board for review and approval of testing protocols, technology acquisition processes and recommendations for technology test and evaluation in laboratory and field settings; (2) development of a technology acquisition process; (3) creation of laboratory and field testing and evaluation capability; and (4) testing of candidate technologies for insertion into a water early warning system. The initial phase of this study involves the development of two separate but complementary strategies to be reviewed by the advisory board: (1) a technology acquisition strategy, and (2) a technology evaluation strategy. Lawrence Livermore National Laboratory and Sandia National Laboratories are tasked with the first strategy, while Los Alamos, Pacific Northwest, and Oak Ridge National Laboratories are tasked with the second strategy. The first goal of the acquisition strategy is the development of a technology survey process that includes a review of previous sensor surveys and current test programs and then the development of a method to solicit and select existing and emerging sensor technologies for evaluation and testing. In this paper we discuss a survey of previous efforts by governmental agencies and private companies with the aim of facilitating a water sensor technology acquisition procedure. We provide a survey of previous sensor studies with regard to the use of Early Warning Systems (EWS) including earlier surveys, testing programs, and response studies. In the project we extend this earlier work by developing a list of important sensor specifications that are then used to help assemble a sensor selection criteria. A list of sensor technologies with their specifications is appended to this document. This list will assist the second goal of the project which is a recommendation of candidate technologies for laboratory and field testing.

2 Introduction

The security of our nation's water distribution systems is a major concern especially 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 their water distribution systems that led to an early evaluation of these types of threats (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 the water monitoring sensor survey and technology-acquisition study presented herein.

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 have been evaluated. 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 few of the military, federal, state, local, and privately funded studies examining 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 both physical security and through water monitoring and emergency response, which is the focus of this study and begins with the non-trivial process of sensor selection. In this document we present a survey of the 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 representative 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 for sensor selection. As an appendix to this study, we present a compiled database of commercially available monitoring technologies and evaluate these technologies keeping in mind the issues that are paramount for the end-user, the water utilities of large and small communities.

3 Water Monitoring Sensor Technology Survey

By compiling and reviewing a survey of previous and on-going studies of EWS, sensor technologies, and testing programs, we hope to provide an overview of the different options and constraints that are 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).

3.1 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, unsurprisingly, a commonality of issues within all of these 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 in a contamination event.
- The understanding that distribution system contaminant transport modeling is an important component in 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.

While the foregoing needs have been identified, the answers often are not straightforward and are continually evolving. Listed below and tabulated in Table 1 are the findings from each report to help establish the extensive effort already expended by different agencies.

ILSI Report (1999)
The International Life Sciences Institute (ILSI) published in 1999 their findings from an ILSI workshop that focused 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 threats; vulnerability; EWS requirements; EWS design; monitoring chemical, radioactive, and microbial contaminants; data interpretation and emergency response. The results from this workshop illustrate that, even prior to the events of September 11, water monitoring for contamination was a significant and important topic.

AWWA (2002)
In 2002, the American Water Works Association (AWWA) published extensive findings from a study of online monitoring for drinking water utilities which was funded by AWWA Research Foundation (AwwaRF) and CRS PROAQUA. This study identified the following: (1) the need for online monitoring; (2) specifications and testing of online monitors; (3) 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 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 a comprehensive analysis 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 determination 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 exercising the system.

Table 1. Previous Design Standards and Surveys

Study	**Comments**	**Reference**
ILSI Report	Pre September 11	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 national water company in the Netherlands) conducted the Early Warning Monitoring project and presented the results in a 2004 final draft titled *Early Warning Monitoring in the Drinking Water Sector*. This document details a significant effort to develop an overview of sensor development and identify the developments that are potentially applicable as early warning techniques. The document provides the following: (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 are a good example of the necessary role of hydraulic modeling in assisting the determination of the distribution of a contaminant and the relationship between the number of sensors and the overall impact of a contamination event.

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

for that workshop discusses their 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 that need to be addressed to improve the security of water distribution systems.

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 if the sensor has the appropriate sensitivity and accuracy for the proposed application. A deployable sensor must be able to provide useable data, and it must be able to detect a sudden change in concentration/measurement over baseline rather than simply detect an absolute measure of the concentration. 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 and the identity and concentrations of a specific contaminant is not established (ASCE, 2004).

Table 2. Sensor Testing and Evaluation Programs

Testing Agency	Testing Program	Comments	References
EPA	ETV Advanced Monitoring Systems Center	Voluntary vendor participation, chem./bio, stakeholder oversight, bench-scale & field-scale	Technical Contact: Eric Koglin
EPA	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 that includes 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 or with chemical classes of contaminants. Additionally, sensor-response under the highly variable conditions of actual water distribution systems is not being measured in these testing programs. These 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 of properly locating sensors within an EWS (Hasan et al, 2004). Additional physical requirements warranting consideration include 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 are often employed to assist sensor siting and placement and to analyze potential and actual threats (e.g., the EPA TEVA Program which uses EPANET with an ensemble approach, Murray, 2004). To use these tools, water utilities need to 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. Combining the details of the 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 network model can track contaminant movement within a pipeline distribution system. A simple example of a small and closed water distribution system demonstrates of 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). Network models help to identify for the specific system 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). Tradeoff decisions will have to be made to balance the cost of sensor placement with human health effects. An added benefit to hydraulic/contaminant-transport modeling is the assessment of potential water distribution threats, contamination event response, and contamination event reconstruction. The utility of these hydraulic models illustrate how greater resources are needed for water-utilities to improve models of their system where necessary in order to optimize sensor placement decisions and emergency response plans.

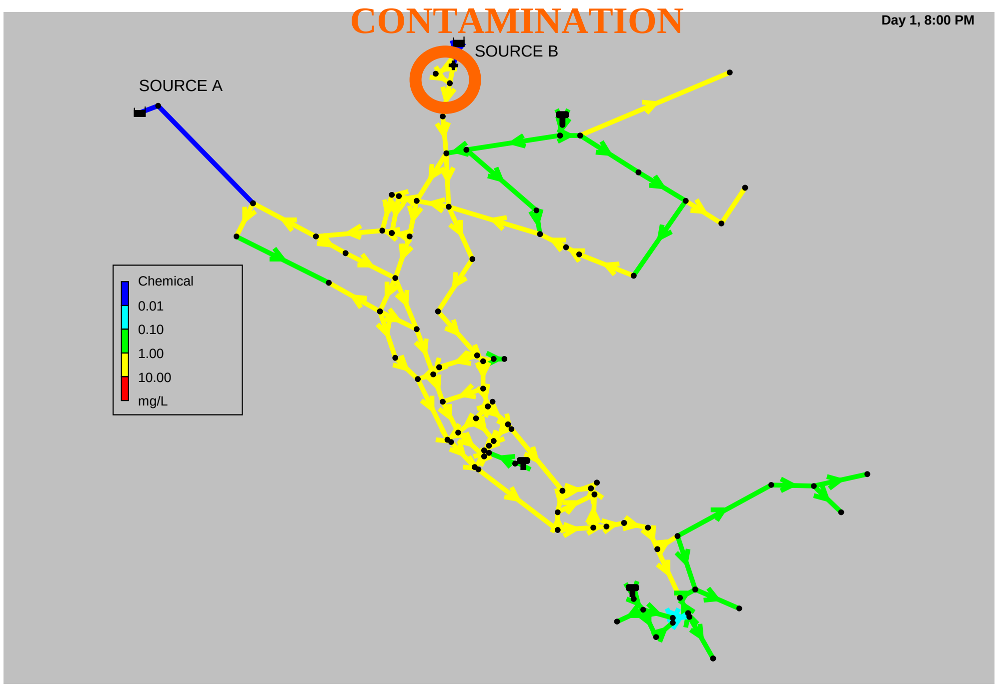

Figure 1. A water distribution system experiencing a wide dispersal of low contaminant concentrations (modeled using EPANET in Glascoe, 2004).

3.5 Review of Response to Sensor Alarm

Once sensors are selected, located, and monitored, the water utility needs to understand the sensor response to changes in the water system and, more importantly, needs to know when and how to react to the sensor-reading. 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, seasonal and system temperature and pH.

3.5.1 Detect-to-warn and Detect-to-treat

As part of an EWS system, 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 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 currently be implemented. However, sensor technologies and control systems are that could improve response times are being developed (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. This requires a reduction in the likelihood of false positives, a source of public distress and distrust. 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-hour 7-days a week staffing of an emergency response center where staff can rapidly evaluate the real time sensor data streams and make appropriate emergency response decisions.

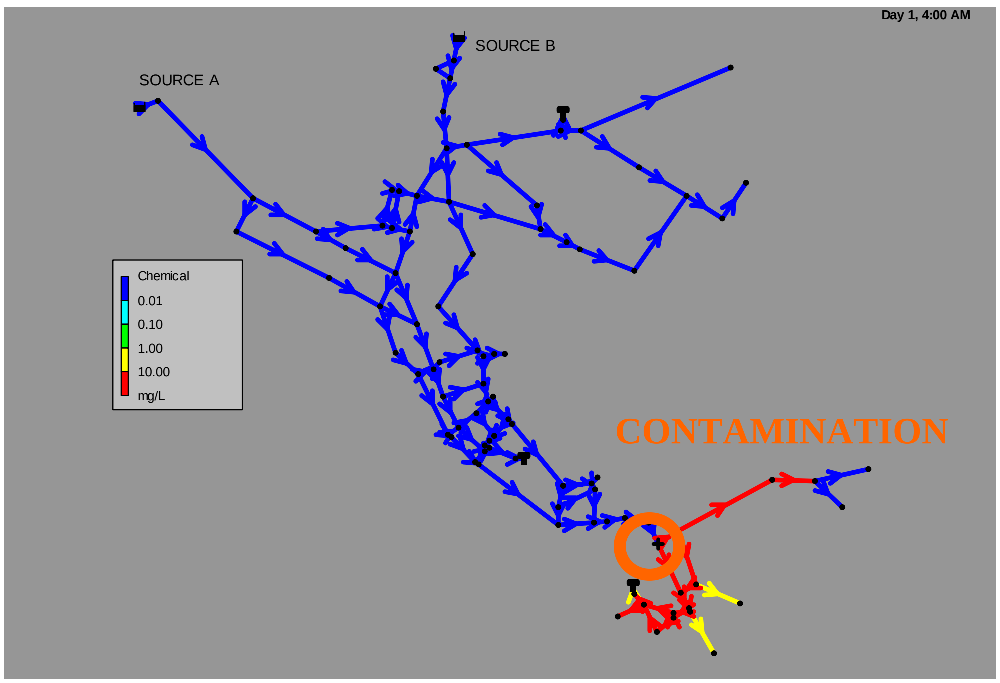

Figure 2. A water distribution system experiencing limited dispersal of high contaminant concentrations (modeled using EPANET in Glascoe, 2004).

3.5.2 Distribution System Response

When a sensor signals a change in water conditions, a realistic response protocol needs to be in place. Basic choices are to shut down the system, divert/isolate the water, or 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. Modern distribution systems have numerous interconnected flow paths. Therefore to divert or isolate potentially contaminated water, a rapidly controllable system needs to be developed over the entire distribution network. Such modifications necessary to a distribution system could involve significant and expensive changes to the infrastructure including re-routing pipe networks and installation of diversion storage tanks/reservoirs. Alternatively, water within a distribution system can be flushed-out by opening fire hydrants. However, this option flushes contaminated water from a closed system introducing 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 response options discussed, valves need to be locatable and completely closeable. In all of these cases, water availability to the public would be severely compromised. 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-reponse and sensor-complexity (Figure 3). Tier 1 sensors are typically a rapid response technology that continuously monitor 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 laboratory analysis that are usually associated with forensic analysis conducted well after the contamination event has occurred. As this survey is concerned with EWS we will focus mainly on Tier 1 and some Tier 2 sensors and will not focus on Tier 3.

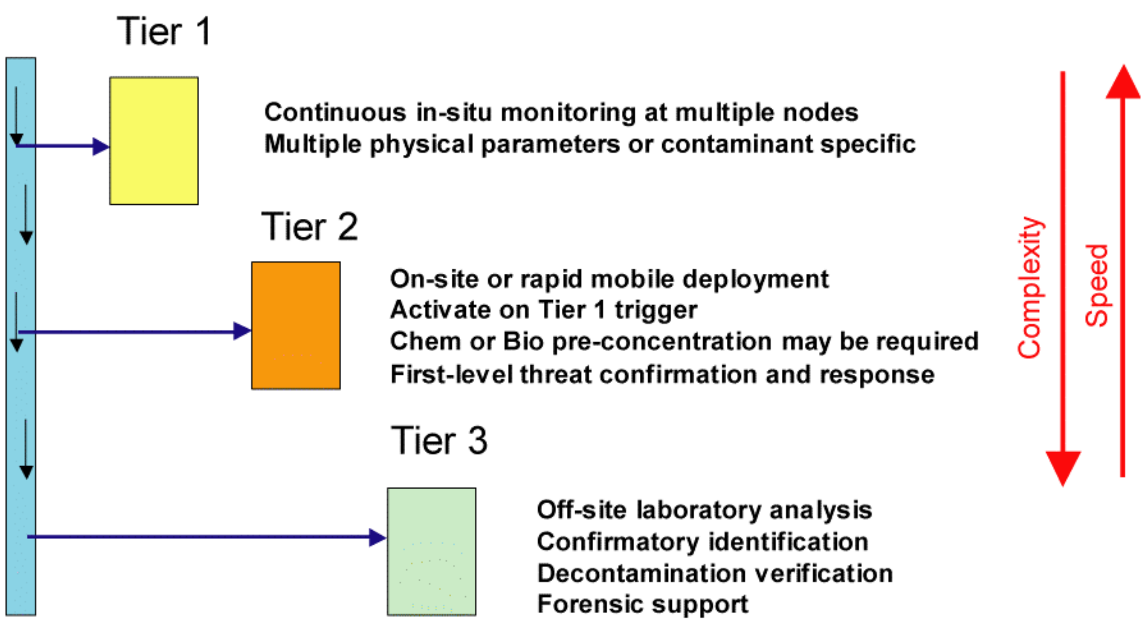

Figure 3. A multi-level monitoring strategy consists of three tiers of technology of varying speed and complexity.

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 characteristics that have been identified from our review of the technologies. The parameters listed in Table 3 are employed to help catalog sensor technologies for our database and are useful to illustrate important differences between sensors. The Appendix contains 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. These sensor acquisition criteria are based in large part on previous water-sensor criteria previously established by other organizations (ASCE, 2004; KIWA, 2005; AWWA, 2002) and are a refinement of those earlier criteria.

Our sensor recommendations result from the realities of water-utility wants and needs, the available sensors, and the expected system implementation. 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.

The important points gleaned from our survey 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. Thus, 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.

Table 3. Sensor acquisition parameters.

Sensor Specification	**Range**
Sensor Cost	($100 to $20000)
Maintenance Requirements	Low, Moderate, High
Operation Requirements	Low, Moderate, High
Technology Group	(See description below)
Specific Technology	(See description below)
Monitored Parameters	(single, few, many)
Response Time	(slow, moderate, fast)
Detection Range/Sensitivity	(fine, moderate, coarse)
Calibration complexity	(high, medium, low)
Calibration stability	(high, medium, low)
Data processing capability	(low, medium, high)
Routine maintenance frequency	(high, medium, low)
Architecture	(in-line, slip-stream, grab-sample)
Sampling cycle	continuous or periodic
Triggered Sample	(Yes, No)
Rate of False +/-	(low, moderate, high)
Life expectancy	(years)
Personnel Training	(easy, moderate, difficult)

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 on discussion with water utility representatives, sensor technology representatives, and largely 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 Table 3 parametric specifications.

Sensor 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 that 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 below). 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 of the individual distribution system need to be included in the assessment.

Operating Conditions/Durability

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 as to their durability and ability to handle fluctuating environmental conditions over time. 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. Therefore such information is important to determine in selecting the appropriate sensor technology for each location within a distribution system.

Maintenance Requirements

In addition to the purchase price of the sensor (see above) and operational costs (see below), sensors installed within a distribution system will require periodic maintenance with an associated cost. Depending on the availability of personnel and resources, the maintenance requirements can often be the most significant cost of a sensor. While it is impossible to accurately assess the true costs of maintenance for each sensor in each distribution configuration, we have attempted to group maintenance cost 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 given application.

Operation Requirements

Sensors installed within a distribution system will have regular costs associated with the requirements for normal operation in addition to sensor maintenance and sensor purchase price. 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. 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 cost 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 given application.

Range of Operation/Performance

Water sensors may come in contact with a wide range of conditions, and it is important to ensure that the range and performance of 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; therefore, 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, and 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.

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 such groups can be obvious for some sensors, they require some judgment for other sensors. 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" category (see below). In the case of multi-parameter sensors, Multi Parameter is listed as the Technology Group.

Specific Technology

Although there may be some similarity between different sensor technologies, some attempt will be made to make distinctions, where available. This information is included to assist with understanding specific sensor differences in the cost and performance criteria within a given Technology Group. For example, within the "Electrochemical" Technology Group, conductivity specifically can be monitored using an "Inductive Cell" or a "Toroidal" measurement. Typically, the nomenclature used in the Specific Technology category did not change when a Multi Parameter instrument was included because the particular technology could be matched with the individual parameters.

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.

Multiple or individual parameters

Some sensors are capable of detecting multiple specific contaminants or multiple non-specific aqueous conditions simultaneously. Sensors that can detect multiple contaminants utilize technology to separate the various contaminants into distinct signals, whereas sensors that detect multiple non-specific changes in aqueous conditions utilize multiple sensors configured into a single installation platform. Therefore, these sensors would provide more information at each installation point than a sensor that detects one water quality parameter only.

Response time

The sensor response time is critical to 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.

Detection Range/ Sensitivity

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 a distribution system infiltration.

Architecture: In-line, grab sample, or slipstream

We 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 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.

Sampling Cycle
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. .

Triggered Sample
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.

Rate of false negatives/positives
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 to do not advertise the rate of false positives or false negatives.

Life Expectancy
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 would 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 costs between sensor cost and life expectancy need to be evaluated for each specific utility's needs.

Personnel training requirements
Generally speaking, water utility operation and maintenance is 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 greatly preferred. Training requirements for technicians should be minimal and easily understood.

4.3 Sensor Selection Requirements
As part of the "Task 1" component of this Department of Homeland Security funded OTD project, we receive guidance from a project Advisory Board. Table 4 lists the 69

specific guidance 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 is currently not a detect-to-warn system, 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, but in our survey, we did discover numerous promising sensor technologies that are in development. These technologies are primarily focused on rapid detection that 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 needed for a 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, if a detect-to-warn system is the eventual goal, significant thought and financial investment must be made to incorporate the necessary changes into new distribution systems, as well as 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 distributions system; it also requires that appropriate action can be taken to minimize the loss of life from a deliberate contamination event. The decisions for appropriate response actions will be different depending on the configuration of the distribution systems and will need to have appropriate governmental and professional coordination and guidance to develop a consistent methodology for providing protection.

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 are commercially available. These few available in-line sensors generally measure surrogate parameters rather than specific contaminants.
- 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, 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 to react to contaminated water distribution systems need to further development.
- A technology gap between current sensor technology and needed sensor technology exists. 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 work within the water utilities' available resources.

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8 Appendix: Compiled Database of Sensors

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