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Safeguarding The Security Of Public Water Supplies Using Early Warning Systems: A Brief Review

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Water distribution systems are vulnerable to aqua-terrorism (terrorism attacks on the water supply) because they are extensive, relatively unprotected, accessible, and often isolated (USEPA 2002, 2003a, Grayman, 2002; Mays, 2004). An emerging activity in the water security arena is developing methods to minimize the public health and economic impacts of a large-scale attack. An intense effort is currently underway to improve analytical monitoring and detection of biological, chemical, and radiological contaminants in drinking water systems as part of the overall effort to secure drinking water supplies (USEPA, 2003b).

One approach for avoiding or mitigating the impacts from contamination of a distribution system is to perform monitoring in the context of an Early Warning System (EWS). At present, federal agencies, academic communities, and private companies are working together to develop practical and effective early warning systems. The goal of an early warning system is to reliably identify low-probability/high-impact contamination events in a distribution system's finished water, or in source water, in time to permit an effective local response that reduces or avoids entirely the adverse impacts that may result from such an event. The core of an EWS is a monitoring technology that, ideally, would detect or screen for a variety of toxic substances or infectious microorganisms (Brosnan 1999; USEPA 2002).

This article briefly reviews the essential elements of an EWS, the relevant plans for developing and implementing an EWS, and the current status and potential for an EWS to ensure the security of drinking water supplies and systems.

The Early Warning System Concept

Though early warning systems are frequently equated with the monitoring instrumentation used to detect contaminants in water, an effective EWS is, in reality, an integrated system for deploying the monitoring technology, analyzing and interpreting the results, and utilizing the results to make decisions that protect public health while minimizing unnecessary concern and inconvenience within a community. Ideally, an EWS should be an integral part of the operation of a water system. It should be able to be used to detect not only intentional contamination, but also contaminants introduced accidentally or as the result or natural occurrences (i.e., dual use capabilities).

A recent American Water Works Association Research Foundation (AwwaRF) study concluded that an effective EWS should include the following components (Grayman et al. 2001):

1. A mechanism for detecting the likely presence of a contaminant in the finished water;
2. A means for confirming the presence of the contaminant, determining the nature of the contamination event and the intensity (concentration) of the contaminant in the drinking water distribution system, and

predicting when the contamination will affect the end users;

3. Communication linkages for transferring information related to the contamination;
4. Various mechanisms for responding to the presence of the contamination in the finished waters in order to mitigate its impacts on water users; and
5. An institutional framework, generally composed of a centralized unit that coordinates the efforts associated with managing the contamination event.

Characteristics of Early Warning Systems

The following guidance is provided for utilities that may consider implementing an EWS using existing technologies, or technologies that will likely enter the consumer market within the next few years. As various technologies and systems are considered, one may wish to evaluate how they compare to the characteristics of an ideal EWS, as described in a recent report by International Life Science Institute (Brosnan 1999), as follows: (1) exhibits warning in sufficient time for action, (2) provides affordable cost, (3) requires low skill and training, (4) covers all potential threats, (5) identifies the source, (6) demonstrates sensitivity to quality changes at regulatory levels, (7) gives minimal false positive or negative responses, (8) exhibits robustness, (9) allows remote operation, and (10) functions year-round.

Currently, an EWS with all of these features does not exist. However, there are some technologies that can be used to build an EWS that can meet certain core criteria: (1) provide rapid response, (2) screen for a number of contaminants while maintaining sufficient sensitivity, and (3) perform as automated systems that allow for remote monitoring. Any monitoring system that does not meet these minimum criteria should not be considered an effective EWS. Although an emphasis is placed on these three features, the other issues discussed above cannot be ignored in the design of an EWS. For example, consideration should be given to the rate of false positive/false negative results and method sensitivity when interpreting the results. Furthermore, system costs, sampling rate, and reliability should also be included in the design of an EWS (Grayman et al. 2001, 2004; USEPA 2002).

Design Considerations for an Early Warning System

An Early Warning System should be integrated into the operation of a water system. Therefore, an overall context for decision making relative to EWS may be viewed as one of designing and operating the system to minimize the risks associated with degraded drinking water quality, under various cost and technology constraints. Designing an EWS is not simple because there are many issues and water system characteristics that need to be considered. These EWS design considerations are discussed in various sources (Brosnan 1999; Clark et al. 2004; Foran and Brosnan 2000; Grayman et al. 2001, 2004; USEPA 2002;) and are briefly summarized below:

Planning and Communication. Before initiating an early warning monitoring program, the objectives of the program should be defined clearly, and a plan should be developed for the interpretation, use, and reporting of monitoring results. Furthermore, the plan should be developed in coordination with the water utility, local and state health departments, emergency response units, law enforcement agencies, and local political leadership.

System Characterization. The first step in the design of an EWS is to fully characterize the system to be monitored such as the distribution system infrastructure. The system should be characterized with respect to access points, flow and demand patterns, and pressure zones. If not already available, a hydraulic model should be constructed. Finally, system vulnerabilities should be identified and characterized, preferably through a formal vulnerability assessment as described previously by EPA (USEPA 2002). An understanding of each of these characteristics provides the backbone for the proper design and development of an EWS. In addition, system characterization should consider both water demand and water usage patterns.

Target Contaminants. An ideal EWS should be capable of monitoring for all potential contaminants. However, even the most complex array of monitoring equipment cannot detect the entire spectrum of agents that could pose a threat to public health via contaminated water. Thus, the design of an EWS should focus on contaminants that are thought to pose the most serious threat. Many factors may go into this assessment, including: the concentration of a particular contaminant that is necessary to cause harm, the availability and accessibility of a contaminant, the persistence and stability of a contaminant in an aqueous environment, and the difficulty associated with detecting a contaminant in the water. System vulnerabilities and the ability of existing treatment barriers to remove or neutralize specific contaminants should also be considered in the threat assessment.

A challenge in designing an effective EWS is striking a balance between the screening function of the system (i.e., the ability to detect a wide range of contaminants) and specificity (i.e., the ability to positively identify and quantify a specific contaminant). One approach to resolving these conflicting objectives is through *tiered monitoring*. In a tiered approach with two stages, the first stage might provide a continuous, real-time screen for a range of contaminants that could pose a threat to public health, utilizing a broad-based screening technology such as assays designed to detect changes in toxicity. A positive result from the first stage would trigger confirmatory analysis using more specific and sensitive techniques, and a positive result from the confirmatory analysis would trigger a response action. Additional discussions of tiered monitoring are presented elsewhere (Daughton 2001). A common misconception is that the screening stage alone of a monitoring system constitutes an EWS. However, a properly designed EWS should include all elements of a monitoring program necessary to inform the decision making of officials responsible for public health. Thus, confirmatory analyses used to verify a positive result from a screening analysis, and the hydraulic modeling or analysis that determines the sampling locations, should be integrated into the overall design of the EWS.

EWS Technology Selection. Once target contaminants for the EWS have been identified, it is necessary to select a monitoring technology for the particular contaminant or class of contaminants, if one that meets the core requirements of an EWS exists. The monitoring technology should be capable of dealing with complex water matrices. This may require an extraction step to remove the material from the water matrix and/or a concentration step to enhance detection and quantification. Although techniques for isolating, concentrating, and purifying microbial and chemical substances have been developed for many laboratory methods, they may not necessarily be transferable to field deployable monitoring devices. The technology considered for use in an EWS should be evaluated to ensure that all steps of the methodology perform correctly and can detect the target contaminant(s) without excessive interference.

Identifying a field deployable technology with an acceptable methodology is only the first step. Performance of the monitoring technology must also be adequate to meet the data quality objectives of the monitoring program. These data quality objectives should be defined during the design of the EWS and include: specificity, sensitivity, accuracy, precision, and recovery, as well as rates of false positives and negatives. If the monitoring technology cannot meet the data quality objectives, then another technology should be selected. If no technology can be identified that meets the objectives, then either the EWS should not be implemented, or the data quality objectives will need to be revised. If the later approach is taken, it will be necessary to modify the manner in which the results are used to be consistent with revised data quality objectives.

Alarm Levels and Response. Once the EWS technology has been identified, it is necessary to identify the concentrations at which the agents pose a threat to human health so that alarms can be triggered at appropriate levels. The basis for setting alarm levels will depend on the capability of the EWS employed. It should also be noted that the alarm should be triggered by a combination of events, not a single detection, which may be a false positive. Many responses are possible when an early warning monitoring system triggers an alarm. Responses may include modification to the drinking water system (e.g., shutdown, addition of disinfectants, etc.), notification (e.g., boil water advisory) either to the general public or to target communities or subpopulations, additional data gathering or monitoring, follow-on surveillance and epidemiologic studies, no action, or some combination of these. The type of response will be dependent on the nature of both the threat to and the nature of the drinking water system, including the population it serves. Where an EWS is in place, credibility of the threat may be judged by the performance of the EWS itself, when it is capable of detecting the contaminants included in the threat. Additionally, law enforcement representatives may provide insight into the credibility of the threat (Foran and Brosnan 2002). If a false alarm leads to a decision to issue a notice to the public to stop using the water, public health as well as public confidence could be impacted.

Fate and Transport of Pathogens and Chemicals. Chemical and microbial agents can behave in a variety of ways as they migrate through a water system. Environmental conditions, the presence of oxidants or other treatment chemicals, and the hydraulic characteristics of the system will affect the concentration and characteristics of these agents. If information is available on agent characteristics that affect their fate and transport, it should be factored into the design of an EWS. For example, if a target agent is known to chemically degrade at a certain rate in the presence of free chlorine, it may be possible to use a hydraulic/water quality model of the distribution system to predict the concentration profile through the system. This information, in turn, can be used to design the EWS and select optimal locations for sensors.

Sensor Location and Density. The location and density of sensors in an EWS is dictated by the results of the system characterization, vulnerability assessment, threat analysis, and usage considerations. The size, complexity, and dynamic nature of distribution systems complicate the selection of sensor locations. Proper characterization of the distribution system, including usage patterns, and the location of critical system nodes (e.g., hospitals, law enforcement and emergency response agencies, government facilities, etc.) is necessary to design an effective monitoring network. Due to their complexity and dynamic nature, it may be beneficial to develop a hydraulic model of the system to assist in the placement of sensors (see the paper by Uber et al, in this issue). Other methods are reported in the literature for optimal placement of monitoring stations (Lee and Deininger 1992; Uber et al. 2004). However, even if sensors can be optimally located within a distribution system, there may not be sufficient time to prevent exposure of a portion of the public to the contaminated water. At best, monitoring conducted within the distribution system will provide time to limit exposure, isolate the contaminated water, and initiate mitigation/ remediation actions.

Data Management, Interpretation, and Reduction. The computer system infrastructure of a medium to large water utility typically includes its financial system, Human Resource (HR) system, Laboratory Information Management System (LIMS), Supervisory Control and Data Acquisition (SCADA) system, Computerized Maintenance Management System (CMMS), etc. The financial, HR, LIMS, and CMMS systems are considered to be part of the utility's Information Technology (IT) infrastructure run by a utility or local government IT group on a daily 8-10 hour schedule. Cyber attacks to the IT infrastructure (i.e., a computer-to-computer attack that undermines the confidentiality, integrity, or availability of a computer or the information it stores) may cause significant financial damage and disruption of the utility's internal operations, but they are not expected to cause immediate water supply disruptions. However, cyber attacks on the SCADA system could have an immediate detrimental impact on the water supply (Panguluri et al. 2004)

One of the challenges of a continuous, real-time monitoring system is management of the large amounts of data that are generated. Use of data acquisition software and a central data management center is critical. This will require that individual sensors deployed in the system be equipped with transmitters, modems, direct wire, or some other means to communicate the data to the acquisition and management systems. Furthermore, the data management system should be capable of performing some level of data analysis and trending in order to assess whether or not an alarm level has been exceeded. The use of "smart" systems that evaluate trends and can distinguish between genuine excursions and noise could minimize the rate of false alarms.

A decision will also have to be made regarding the action that is taken when the data management system detects an excursion above the alarm level. At a minimum, the system should notify operators, public health agencies, and/or emergency response officials. If possible, redundant communication should be used (e.g., notifying multiple individuals through multiple routes such as page and fax). In some cases, it may be appropriate to program the data management system to initiate preliminary response actions, such as closing valves or collecting additional samples. However, these initial responses should be considered simple precautionary measures, and public officials should make judgments regarding decisive response actions.

Existing and Emerging Monitoring Technologies

While laboratory technology exists to measure a wide range of substances in the environment, the analytical capabilities of monitors as part of an EWS are more limited. Currently available water quality monitors include physical, chemical, radiological, and microbiological analysis as well as bio-monitoring systems that use living organisms as broad spectrum indicators of changes in water quality. The use of biosensors has to date been limited to chlorine/chloramines-free source waters. Efforts are underway to adapt biosensors so that they can be employed in public water supply distribution systems. References for commercially available rapid or on-line monitoring techniques for the water industry include AwwaRF and CRS PROAQUA 2002; Frey et al. 2000; Grayman et al. 2001.

Some of the more common physical and chemical monitoring methods proposed for use in EWS include simple probes (e.g., turbidity, pH, temperature, odor, conductivity, dissolved oxygen, chlorophyll); relatively simple batch tests (e.g., immunoassays for herbicides), and more advanced monitoring for chemicals (e.g., fluorescence for oils, chromatography for oil and petroleum constituents, volatile organic chemicals and phenols). Some of the primary contaminant surrogates include turbidity, dissolved oxygen, odor, conductivity, and general measures of organic carbon content (e.g., oxidant demand, total organic carbon). However, the parameters that are easily and inexpensively monitored via on-line probes (e. g., temperature, conductivity, pH) provide limited capability for detection of specific contaminants of security concern. Advanced monitors are more expensive and require more maintenance and expertise, but have better capabilities for these applications. Based on recent research in the food and chemical industry, electronic odor sensing technologies ("electronic noses") may be available in the future for use in the analysis of water (Grayman. et al. 2001).

Conventional culture methods for detecting microbial contaminants require a relatively long time period (hours or days) and many tests are specific for a single species or class of organism. As such, these analyses cannot be used as part of an EWS. However, numerous significant recent advances in microbial monitoring and related technology offer increased sensitivity, specificity and/or more rapid analysis, including DNA microchip arrays, rapid DNA probes and PCR, rapid hand-held immunoassays, cytometry, laser scanning, laser fingerprinting, optical technologies, and luminescence (e.g., bio- and chemi-luminescence) (Foran and Brosnan 2000; Grayman et al. 2001; Lee and Deninger 1999; Rose and Grimes 2001; States et al. 2004; Venter 2000). More recently, concentration of water samples by ultra filtration followed by PCR is carried out by Vince Hall at CDC and others (Gelting 2004). Most of these methods are still being developed or were only recently introduced. Their use, however, is likely to increase in the future.

An example of a promising approach for continuous monitoring of water for multiple pathogens is the Automated Pathogen Detection System (APDS) being developed by the Lawrence Livermore National Laboratory. This system traps analytes of interest onto antibodies conjactaed to beads with subsequent identification through fluorescence. While this immune separation assay has been primarily designed for aerosol monitoring, it may be adaptable to pathogen detection in water supplies if the aerosol monitor is replaced with a large volume water concentration system.

In general, while prototype systems for monitoring airborne contamination are in use at various locations around the country, systems for detecting microbial pathogens in drinking waters supplies lag behind.

Research and Development Needs

A number of ongoing research projects of AwwaRF and the Water Environment Research Foundation are investigating rapid and on-line monitoring technologies. Many of the advances in monitoring technologies occur from research in other scientific fields (e.g., the food and beverages industry, analytical chemistry, the sensor industry, and the military), including biosensor and biochip technology, fiber optics, genetically-engineered organisms, rapid immunoassays, microelectronics, and others. Several U.S. government organizations, including the USEPA and the U.S. Army's Joint Service Agent Water Monitor Program, are conducting research on rapid and/or on line monitoring systems for a variety of contaminants.

A number of monitoring technologies and products are available that could potentially serve as a core component of an EWS, and a number of suppliers of conventional monitoring systems have begun to advertise them as water security monitoring systems in the wake of terrorist concerns. However, the performance of these systems has not been fully or independently characterized in most cases. Without basic performance information (e.g., detection limits, sensitivity, selectivity, rate of false positives and false negatives), it will be difficult to interpret monitoring results and derive the information necessary to make appropriate public health decisions.

As promising technologies continue to be developed and brought into the commercial market, there is a need for a mechanism, including field evaluation and testing sites, to verify system performance. Ideally, such testing should be conducted according to a standard protocol by an independent third party, and the subject technology should be evaluated against standardized methods, if available. This would provide water utilities with the data necessary to make informed decisions regarding the implementation of a specific technology in an EWS. EPA has established the Environmental Technology Verification (ETV) Program to provide independent third party testing of environmental monitoring and treatment technologies. Under the Advanced Monitoring Systems Center of ETV, monitoring technologies with the potential to serve as an EWS in water systems will be evaluated, and the reports will be made available to the public.

Conclusions

An early warning system must reliably identify low-probability/high-impact contamination events in distribution systems or source water in time to allow for an effective response. The type of response and the method of communication of the response will depend on the nature of the threat, the capabilities of the EWS itself, and on the characteristics of the affected population. Especially critical is the development of an emergency preparedness plan that guides the responses associated with a signal from the EWS and the communication of actions based on the responses (Foran and Brosnan 2000).

The resources necessary for the development, installation, operation, and maintenance of an EWS will be substantial; therefore, virtually all of the decisions regarding the EWS must be made at the local or regional level.

Implementation of some types of existing monitoring technology will result in a false sense of security since there is no assurance that they are capable of meeting the monitoring objectives. In addition, these systems could result in false alarms that would undermine the effectiveness of a monitoring program and result in a needless expenditure of resources to follow-up on the false positive and false negative results (USEPA 2002).

To ensure the full protection of drinking water, a technology-based early warning monitoring system should be just one component of a comprehensive program to protect the public from the threat of intentional contamination. The program must also include physical, social, and economic steps to prevent the problem, as well as public health monitoring to ensure that early detection of disease will occur if a monitoring system or other steps fail (Brosnan 1999; Foran and Brosnan 2002; USEPA 2002).

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