Drinking water systems serve communities with a consumable product that is assumed to be safe and reliable. However, drinking water systems are largely vulnerable to attack, even by fairly amateurish means. The need to develop and implement defenses against contamination that can be introduced into drinking water distribution systems is clear, yet there are few examples of real security improvements that have been developed and implemented during the last 60 years.

The same drinking water considered to be safe and reliable is also responsible for transmitting pathogenic organisms and toxic chemicals that result in thousands of illnesses annually—without malevolent action. In defense of the drinking water industry, the occurrence of these illnesses per capita is fairly low and is, in any case, a significant improvement from 100 years ago. However, such relatively mild contamination illustrates both the vulnerability of water distribution systems and the long-overdue need to develop and implement defenses against contamination that can be introduced to the distribution system.

The US military has long worked to protect military drinking water resources, and the civilian section can gain from its experiences. The study presented in this article is based on surveying various military drinking water systems for vulnerabilities to natural events as well as to enemy attacks or sabotage.

The objective of this study is to utilize commercial distribution system modeling software to understand how a drinking water system could be impacted by the intentional introduction of chemical contaminants. Four highly toxic chemicals—parathion, VX, sodium monofluoroacetate (1080) and cyanide—were selected, and water quality models of various scenarios were used to determine the influence of feed methodology, location, and the chemical itself on the effect of contamination. The model results were then combined with concentration-response sensitivity data from routine monitoring instruments to determine the ability of each chemical contaminant to be detected. Because all of the

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chemicals were modeled as highly persistent, their comparative effects were determined by the toxicity of the highest practical dosage.

**HISTORY REVEALS VULNERABILITY**

**Drinking water systems are at risk.** Drinking water systems face a variety of threats today. Physical damage or destruction to water facilities could deny service to individuals, commercial enterprises, and industries, with a potentially devastating impact on fire protection and medical care. Contamination of drinking water could be done with the intent to deny service, create panic or loss of public confidence, and/or to cause death or illness to a population (Haimes et al, 1998).

Drinking water systems are clearly among the most vulnerable and desirable targets for terrorists seeking to inflict mass casualties. At least one evaluation of the threat indicates that there is no easier way for a terrorist to disseminate a chemical or biological agent than through the intentional contamination of food or water supplies (Khan et al, 2001). Under the right conditions, only a few grams of pathogenic organisms are needed to produce sporadic illness in the population served by a water system. If adequately mixed, 1 g of feces in 1 mil gal (3.785 ML) of water could create a 10% chance of rotavirus infection if 1 L (0.26 gal) of the water is consumed (Rose, 2002). Chemicals create a similar threat to drinking water. Although in many cases large quantities of chemicals would be needed to create a toxic effect, there is no lack of chemicals such as insecticides, solvents, corrosives, and caustics that can be easily obtained in sufficiently large quantities.

It is a certainty that the vast majority of drinking water systems are easily accessible. The National Research Council’s Committee on Science and Technology (2002) concluded:

The water infrastructure enjoys little physical protection. Much of the supply, transportation, and distribution system is unstaffed and readily accessible to the public. New methods for physically securing the system are needed, as are ways of continuously—or at least periodically—monitoring for intrusion across the large areas that water systems cover.

The vulnerability of drinking water facilities to vandals, many of whom are juveniles, helps to illustrate how easily the facilities may be accessed. One study chroni-

### TABLE 1 Examples of recent destructive acts against United States and Canadian water utilities

<table>
<thead>
<tr>
<th>Date</th>
<th>Incident</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 2003</td>
<td>At the DeBary, Fla., water treatment plant, an unknown person or persons crossed a barbed-wire fence, broke open an entry gate, and removed aerator screens. State officials reviewing the case described it as a “professional job” that could have affected the water in more than 4,000 homes. The utility was eventually fined by the state for violating a newly enacted law requiring notification of the health department of such break-ins within 24 h.</td>
</tr>
<tr>
<td>June 2002</td>
<td>Workers at a Janesville, Wis., water utility discovered that the barbed wire on a recently installed fence and the padlock on the 5-mil-gal elevated storage tank had been cut. Although no evidence of contamination was found, the tank was drained and superchlorinated.</td>
</tr>
<tr>
<td>May 2002</td>
<td>Juveniles were suspected in a case of vandalism at the water pumping station in Dawson, Iowa. Chemicals were found splattered inside the building, and computers were damaged.</td>
</tr>
<tr>
<td>July 2001</td>
<td>An emergency was declared in the Vancouver Island town of Ladysmith, B.C., when workers found a reservoir hatch open and an oily substance on the surface of the water. The 6,400 residents were warned not to use the water until the system was flushed. Earlier in 2001, hatches were removed from the municipal reservoirs in two nearby towns.</td>
</tr>
<tr>
<td>October 1999</td>
<td>Two juveniles were suspected in pouring a “bright red substance” into the water supply at the Grass Valley, Calif., water treatment plant, causing denial of service to 2,300 customers.</td>
</tr>
<tr>
<td>1998</td>
<td>Juveniles had planned to enter the Neenah, Wis., water treatment plant in order to dump dry soap into the filters, to dump liquid soap on the floors, and to lay trip wires to inhibit plant workers.</td>
</tr>
</tbody>
</table>

Sources: Voyles-Pulver, 2003; Carpenter, 2002; Probasco-Sowers, 2002; Canadian Press, 2001; Cox, 1999; Wettering, 1999

### TABLE 2 Parameters for metered contamination scenario

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Toxic Goal</th>
<th>Target Concentration mg/L</th>
<th>Feed Conditions g/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parathion</td>
<td>Maximum solubility</td>
<td>24 (at minimum hourly flow)</td>
<td>1,260*</td>
</tr>
<tr>
<td>VX</td>
<td>4 × LD₅₀</td>
<td>4 (at maximum hourly flow)</td>
<td>1,008*</td>
</tr>
<tr>
<td>1080</td>
<td>LD₃₀</td>
<td>240 (at maximum hourly flow)</td>
<td>1,000†</td>
</tr>
<tr>
<td>Cyanide</td>
<td>LDₐ₀</td>
<td>171 (at maximum hourly flow)</td>
<td>370†</td>
</tr>
</tbody>
</table>

1080—sodium monofluoroacetate; LD₅₀—50% lethal concentration dose; LDₐ₀—lethal dose, low

*Pure product
†Dissolved
cluded 833 actual acts of destruction against US public utilities between 1986 and 1995 (Kunze, 1997). Table 1 outlines some of the more recent acts against water supplies in the United States and Canada.

Threats to attack or contaminate drinking water systems are common, numbering in the hundreds annually (Beering, 2002). One example is a threat in October 2002 by the Earth Liberation Front to destroy two 1 mil gal (3.785 ML) water tanks near Winter Park, Colo. (Pankratz, 2002). Perhaps more significant, water supplies have historically been targeted by terrorists, as well as by military forces, during wartime. One example is the arrest of four Morroccan men in Rome in February 2002. The men were found in possession of 4 kg (8.82 lb) of potassium ferrocyanide, detailed maps of the US embassy and the water distribution system for the city Rome, as well as 100 false residence permits (Eldridge & Brown, 2002). Even more recently, Iraqi agents reportedly plotted to poison a water tank that served US troops in Khao, Jordan, but were arrested on April 1, 2003, before they could carry out their plan (Feuer, 2003).

A flurry of activity followed the terrorist attacks on Sept. 11, 2001. The US Environmental Protection Agency (USEPA) formed the Water Protection Task Force on Oct. 5, 2001 to coordinate national water security efforts. On Oct. 16, 2001, the Critical Infrastructure Protection Board was formed to coordinate physical and information security in various sectors. In spite of the longstanding awareness and these recent government actions, Dr. Richard Luthy, chair of the National Research Council’s Water Science and Technology Board, stated before Congress on Nov. 14, 2001, that “the vulnerability of our water systems to attacks has not received sufficient attention” (Luthy, 2001).

**Distribution systems are the most vulnerable.** Although assessments of the threat vary, virtually all authorities agree that the distribution system is the most vulnerable portion of a potable water system. John Sullivan, Chief Engineer for the Boston Water and Sewer Commission and President of the Association of Metropolitan Water Agencies (AMWA) stated, “There’s no question that the distribution system is the most vulnerable spot we have” (Dreazen, 2001). One of the earliest assessments of the threat (Berger & Stevenson, 1955) indicated that the distribution system is a better target than the source if contamination is the goal of an intentional attack. More recently, Deininger (2000) stated that an attack within the distribution system would be more likely to succeed than one against the treatment plant.

The reasons for distribution system vulnerability and its resulting attractiveness as a terrorist target are numerous. Two of the greatest defenses of any water system are its treatment works for removing various contaminants and the dilution factor of the vast volumes of water that are stored and processed. Any attack that occurs downstream of treatment and storage bypasses the water system’s primary defenses, enabling a contaminant to potentially travel unhindered to the taps of consumers (National Research Council, 2002). In most systems, the disinfectant residual is the only remaining defense, which may or may not make a meaningful impact on a highly concentrated contaminant. Contaminants added at the distribution system level

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**TABLE 3** Derivation of contaminant concentration per toxic effect

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Toxic Effect</th>
<th>Dosage mg/kg (lb)</th>
<th>Water Consumed L (gal)</th>
<th>Body Weight kg (lb)</th>
<th>Concentration mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parathion</td>
<td>LD₅₀</td>
<td>3 (7)</td>
<td>0.5 (0.1)</td>
<td>60 (132)</td>
<td>360</td>
</tr>
<tr>
<td></td>
<td>LD₉₀</td>
<td>0.171 (0.377)</td>
<td>0.5 (0.1)</td>
<td>30 (66)</td>
<td>10.26</td>
</tr>
<tr>
<td></td>
<td>Possibly toxic</td>
<td>0.11 (0.24)</td>
<td>2 (0.5)</td>
<td>30 (66)</td>
<td>1.65</td>
</tr>
<tr>
<td>VX</td>
<td>LD₅₀</td>
<td>0.0075 (0.0165)</td>
<td>0.5 (0.1)</td>
<td>60 (132)</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Toxic</td>
<td>0.002 (0.004)</td>
<td>0.5 (0.1)</td>
<td>30 (66)</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Possibly toxic</td>
<td>0.00143 (0.0032)</td>
<td>2 (0.5)</td>
<td>30 (66)</td>
<td>0.02145</td>
</tr>
<tr>
<td>1080</td>
<td>LD₅₀</td>
<td>2 (4)</td>
<td>0.5 (0.1)</td>
<td>60 (132)</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>LD₉₀</td>
<td>0.714 (1.574)</td>
<td>0.5 (0.1)</td>
<td>60 (132)</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>Potentially fatal</td>
<td>0.5 (1.1)</td>
<td>0.5 (0.1)</td>
<td>30 (66)</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Safe dose</td>
<td>0.1 (0.2)</td>
<td>2 (0.5)</td>
<td>30 (66)</td>
<td>1.5</td>
</tr>
<tr>
<td>Cyanide</td>
<td>LD₅₀ (rat)</td>
<td>6.44 (14.20)</td>
<td>0.5 (0.1)</td>
<td>60 (132)</td>
<td>772</td>
</tr>
<tr>
<td></td>
<td>LD₉₀</td>
<td>2.857 (6.299)</td>
<td>0.5 (0.1)</td>
<td>30 (66)</td>
<td>171</td>
</tr>
<tr>
<td></td>
<td>TD₉₀</td>
<td>0.714 (1.574)</td>
<td>2 (0.5)</td>
<td>30 (66)</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Safe dose</td>
<td>?*</td>
<td>2 (0.5)</td>
<td>?*</td>
<td>15</td>
</tr>
</tbody>
</table>

1080—sodium monofluoroacetate; LD₅₀—50% lethal concentration dose; LD₉₀—lethal, low

*Value given as an allowable concentration in drinking water for an adult

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will not have sufficient contact time with the disinfectant residual before reaching many end users. As a result, the effect of disinfection and oxidation will be minimized. Other decomposing processes such as hydrolysis or biodegradation will also have limited time to work (Clark & Deininger, 2001). In the distribution system, lesser quantities of chemicals are needed to create high concentrations of contaminant because there is a significantly smaller volume of water in the distribution system compared with millions of gallons in a storage tank (Dreazen, 2001). The distribution system is also more accessible than treatment plants and storage tanks, particularly because security has been elevated at these facilities across the United States since the terrorist attack on Sept.11, 2001. Access to the distribution system may be obtained from any home, office building, or warehouse through the service line connection. All that is needed to access the distribution system is a small pump that can be obtained from many sources. Provided the contaminant is injected at a higher pressure than the pressure of the service line, the contaminant may cause a reversal of flow back into the water distribution line unless the service line has backflow protection. An attack in this manner can also be covert—the contaminants can be added over many hours or even days, and the only indication would be the resulting widespread illness (Deininger, 2000). This method of attack is believed by many to be the greatest threat to drinking water systems (De Young & Gravely, 2002).

Fire hydrants provide such convenient and numerous access points that they have been called “easy targets” for terrorists. Through a fire hydrant, a tank truck with a pump could overcome the pressure within the system and inject a toxic load of contaminant (Deininger, 2000). Few hydrants in the United States have backflow protection to prevent this from happening, and the equipment required to accomplish this form of an attack may be easily obtained. Given the larger volume of water hydrants are designed to provide, the potential for injecting contaminants in greater quantities through the reversal of flow method exists. Deininger’s (2000) assessment that “a subdivision or street” could be affected from a hydrant, and “a neighborhood” from a service line, appears to indicate that the potential spread from either source is about equal. In addition, given basic hydraulic information for the system, this method could be used to target particular locations, such as defense facilities and high-profile government and commercial buildings. This kind of targeting appears to have been the intent of suspected terrorists operating in Rome prior to their arrest, as cited earlier (Eldridge & Brown, 2002).

Both the likelihood and effect of a waterborne attack by means of backflow can be gauged through the study of accidental backflow occurrences. Concern over the potential effect of an accidental backflow has been great enough to create the American Backflow Prevention Association (ABPA). Backflow has been determined to have caused both illness and death in the United States, including 57 waterborne disease outbreaks causing 9,734 illnesses between 1981 and 1998 (USEPA, 2002). These figures represent 15% of all reported waterborne disease outbreaks (Craun & Calderon, 2001), although a study by AWWA attributes 95% of all disease outbreaks in community water systems to backflow and cross-connections (AWWA, 1999).

Regardless of the exact figures, it is clear that accidental backflow is a significant cause of illness in the United States. Therefore, if accidental backflow is common, it may be concluded that an intentional backflow attack has a high probability of success at causing illness or death. An attack using high concentrations of highly toxic materials may have a more devastating impact than the accidental backflow of more common biological and chemical contaminants.

Interest has grown in researching contaminant detection. The vulnerability of a drinking water distribution system, combined with the heightened risk of an attack designed

**FIGURE 1** Points of injection for modeled contamination

![Diagram of Points of Injection](image-url)
to produce mass casualties, has stirred a great amount of interest in designing adequate defenses for these resources. Because the drinking water system cannot be physically secured, the focus has been on developing a means of monitoring water quality within the distribution system. Recommendations for research into contaminant detection may be found throughout the current literature on infrastructure security (De Young & Gravely, 2002; National Research Council, 2002; Cilluffo et al, 2001; Luthy, 2001). Although all drinking water systems monitor numerous water quality parameters at the point of treatment, far fewer systems perform more than a few required tests in the distribution system. Even fewer accomplish any continuous, real-time analysis that would be necessary for timely detection in order to prevent mass casualties in the event of an attack. In addition, many of the potential contaminating agents do not have sampling and analysis protocols that may be used to detect them.

Before research into detection can proceed very far, more fundamental questions must be answered. First, the credible threat agents to drinking water must be identified and prioritized. The amounts of these chemicals that would constitute a threat must be known. The points in a distribution system that are vulnerable to contamination must be known (National Research Council, 2002; Luthy, 2001). The behavior of the threat agents in water must also be determined. Although a great amount of work has been done to determine the behavior and effects of chemical and biological agents in air, there is very little data for these agents in water (Clark & Deininger, 2001). The effectiveness of chemicals through ingestion of water may be significantly different than that from inhalation or dermal exposure and will largely be determined by the hydrolysis rate.

In addition, to assess the threat to a water system, the hydraulics of the system must be known. Because of the complexity and variability of flows and mixing that occur (Clark & Deininger, 2001), distribution system modeling is needed if the concentration and spread of a contaminant is going to be predicted with any accuracy. Mathematical models have been used successfully to predict contamination concentrations in water systems (Clark et al, 1988), as well as to track contamination to its source (Clark et al, 1996). However, the integration of modeling and real-time monitoring is still a subject for future research.

Modeling and monitoring are also connected by the need to strategically place sensors in order to detect and measure changes in water quality. Methods for optimizing the placement of these sensors have been developed, both for degradation within the system (Lee & Deininger, 1992) and for degradation from an external source (Kessler et al, 1998). Both of these methods rely on a thorough understanding of distribution system hydraulics.

**MATERIALS AND METHODS USED**

A 4-sq-mi pressure zone was modeled. For this study, a water quality model for one pressure zone of a municipal drinking water distribution system was used. The pressure zone covered approximately 4 sq mi in a primarily low-density residential area. The model used a common water distribution modeling and optimization software platform.1 The hydraulics of the model were representative of the actual distribution system hydraulics, but the model was not calibrated to the actual system. (This would not inter-
fere with the results of this study as the intent was to demonstrate the possibility of a chemical contaminant spread and its detection rather than to ascertain the impact to a particular system.) Demand and flow in the model represented average daily conditions (3.9 mgd [14.8 ML/d]); however, actual demand and flow may vary significantly according to the season, day of the week, and other factors.

Accurate modeling required very small time steps, especially when high-volume chemical injection flows were simulated. For the hydrant scenario, a time step of 15 sec was necessary, whereas a 1-min time step was used for the other scenarios. Contaminant injection was begun at midnight, which was the beginning of the lowest period of demand in the diurnal cycle.

The need for and development of water quality modeling was a result of the 1986 Safe Drinking Water Act Amendments that established disinfection by-product standards at the point of consumption. This legislation forced utilities to consider drinking water quality in the distribution system and changes in quality that might occur following treatment (Clark et al, 1995). Degradation in water quality can result from the decay of disinfectant residual, the generation of a contaminant within the distribution system (e.g., disinfection byproducts), or the occurrence of contamination originating from a point source. The usefulness of modeling to predict contaminant propagation was shown by Clark et al (1988). More recently, modeling has been used to track the incidence of disease-causing contamination to its source (Clark et al, 1996).

The reaction kinetics were modeled using two decay reactions: a bulk decay reaction and a pipe-wall decay reaction. The bulk decay reaction represents chemical decay from hydrolysis and chemical interactions such as oxidation of the contaminant. The pipe-wall decay may contribute significantly to the overall decay rate as a result of the effects of corrosion, scaling, and biofilm that may be present on the pipe wall (MWH Soft, 2002). For the purposes of the model, the pipe material was assumed to be polyvinyl chloride (PVC) throughout the distribution system. This was a conservative choice for the purposes of contamination modeling because PVC is non-reactive with most chemicals and does not corrode. Therefore, in a system of PVC construction, the wall reaction may not contribute significantly to the decay of the contaminant chemicals. This was modeled as no decay occurring in the pipe-wall reaction.

Ambient water conditions were selected. Available decay rate data for parathion, VX, and 1080 indicate that chemical hydrolysis and/or oxidation rates decrease as water temperature decreases. For the model, a water temperature of 5°C (41°F) was assumed, which is typical of winter or early spring conditions in many water systems. The results at this temperature would indicate the maximum potential hazard from the chemical being modeled. A pH of 7.9 was selected, which is a typical target for many public drinking water systems to control corrosion. Alkalinity was set at 40 mg/L. This value is low compared with public water systems across the United States, but is typical for water systems using mountain stream sources, such as along the Front Range in Colorado.

Four chemical agents were selected. The four chemicals selected for this study (parathion, VX, 1080, and cyanide) were determined to be significant chemical threats to drinking water. Although there are many other chemicals that could be used to contaminate a drinking water system, this group was selected because each has a range of solubility and toxicities and the contaminants were a mix of inorganic and organic agents.

Testing involved three contamination scenarios. Three different methodologies for intentionally introducing contamination into a drinking water system were tested. The first two scenarios involved continuous covert backpressure feeding of a contaminant into the distribution system through a standard residential ¾-in. diameter service connection. One scenario used a large pump (rated 35 gpm [2.2 L/s] at 155 psi) to create high flows of a dilute-dissolved contaminant under high pressure. The other used
a much smaller pump, often operating at flows of 0.01 gpm (0.0006 L/s) or less, to meter small quantities of a pure or highly concentrated contaminant at just above system pressure. The third scenario used a tank truck with a built-in pump (which is available for purchase online) to unload its contaminated cargo through back-pressure into a fire hydrant in a matter of a few minutes at rates of 750 gpm (47 L/s) or more.

An initial evaluation of these methodologies applied at different locations in the model led to the selection of the low-volume, pure-product-metering approach for further study of its possible impact on the distribution system. This approach was applied at numerous locations in the distribution system with the contaminant feed rate tailored to achieve targeted contaminant concentrations from mixing at the point of entry into the distribution system. Table 2 lists the targeted effects, the needed concentrations, and the feed conditions for the four chemicals. The objective of the selected concentrations is maximum toxicity with minimum indication of contamination.

The goal for all of the chemicals was to achieve a concentration in the distribution system equivalent to a 50% lethal concentration (LD50) dose of the chemical in 0.5 L (0.13 gal) of water. Because of the varying solubility and toxicity of the chemicals, the authors found that not all chemicals could be fed at levels high enough to meet this goal. For example, cyanide was limited for use as a poison by taste and odor concerns—of which the threshold concentrations are unclear and individually variable. Both cyanide and 1080 may be limited by the available quantity that can be obtained, stored, and fed, particularly considering the need for saboteurs to avoid the attention of law enforcement and intelligence agencies. For the purposes of the model, a maximum available quantity of 1,000 lbs (454 kg) was chosen.

Depending on the feed rate needed at individual locations, this limit on the quantity of the chemical supply also placed limits on the length of the contaminant feed operation. This, more than any other reason, led to the reduction of the goal concentration for cyanide, because the duration of the injection would otherwise be too short to affect a large volume of water. In contrast to the other chemicals, the very high toxicity of VX allowed for an increased dosage of four times the original goal, while still using less than 30 gal (114 L) of the chemical.

Contaminant hazards were quantified. In order to quantify the hazard to human health, various toxicological values were needed to determine the effect of a specific concentration of a contaminant. Toxic and fatal doses were selected from the literature and converted to a concentration necessary to achieve the dosage. Table 3 outlines this selection process. In order to convert a dosage in mg/kg to a concentration in mg/L, a value for the quantity of water containing that dose must be given, as well as an assumption about the body weight of the targeted population. The LD50 doses listed in Table 3 were converted to determine the target concentration for this effect. Presuming the intent of the contamination is to affect as many people as possible prior to remedial actions being taken, the target dose (LD50) must be delivered acutely in a single serving (0.5 L [0.13 gal]) and affect an average-sized person (60 kg [132 lbs]). The values at toxic levels in Table 3 other than the LD50 were intended to determine the possible effects at lesser concentrations, which would occur as the contaminated slug of water was mixed in the pipe network. These effects could result from multiple doses and/or in children, so the quantity of water and the body weight factors were adjusted accordingly.

Numerous strategic locations within the distribution system were identified and used to model the injection of contamination (Figure 1), with the contaminant feed adjusted to approximate the contamination goals for the four chemicals at the point of entry into the distribution system. The contaminant spread was then modeled and recorded after 3, 6, 12, and 24 h of injection. The extent of the contamination was quantified according to the proportion of the system demand affected. The model operated using a system of nodes and links that were analogous to pipes and junctions, respectively. Demand is a property of the nodes and can only be applied to the system at these points. The distance between nodes is typically much greater than the actual distance between service connections, which creates some artificiality for the simulation. The extent of the contamination at various concentrations was displayed by use of various contours, which were defined according to toxicological effect. The nodes in the various contour regions were identified by a query, and the demands for each of the identified nodes were summed together and divided by the overall system demand to give a proportion of the service volume affected. A comparison of the results for various injection sites could be used to identify the potential source locations that presented the greatest risk to the system as a whole.

Detection limits were determined. Detection of the contaminants in this study was based on a significant change in a standard drinking water quality parameter. A “significant change” was defined as a variation greater than 3s from the mean value. To establish the statistical basis for this determination, five parameters—turbidity, chlorine, total organic carbon (TOC), pH, and conductivity—with real-time instrumentation in the actual distribution system were measured over a six-day period with data points recorded every minute. The statistics for the data collected are shown in Table 4. Using these five parameters, the primary detection method for the organic compounds was TOC. Given that a 3s variation for TOC concentration is 0.14 mg/L, the detection limits for parathion, VX, and 1080 could be computed from their carbon content by weight (parathion = 0.34 mg/L; VX = 0.28 mg/L; monofluoroacetate = 0.58 mg/L).
Although cyanide is inorganic, the bench tests conducted using TOC analysis illustrated that cyanide is detectable through this method. A precise relationship between cyanide concentrations and TOC results was not calculated because only three data points were measured. However, pH provides an effective method of detection. Using the ambient water conditions mentioned earlier and a pK_a of 9.32 for the acid-base reaction, the pH resulting from a concentration of sodium or potassium cyanide could be calculated using charge balance equations. Given that 3s for pH change is 0.18 and a pH of 7.9 was selected (as noted earlier), the detection limit for cyanide is 8.08 (7.9 + 0.18). Through several iterations, this value was determined to be 0.64 mg/L for sodium cyanide.

Although cyanide is inorganic, the bench tests conducted using TOC analysis illustrated that cyanide is detectable through this method. A precise relationship between cyanide concentrations and TOC results was not calculated because only three data points were measured. However, pH provides an effective method of detection. Using the ambient water conditions mentioned earlier and a pK_a of 9.32 for the acid-base reaction, the pH resulting from a concentration of sodium or potassium cyanide could be calculated using charge balance equations. Given that 3s for pH change is 0.18 and a pH of 7.9 was selected (as noted earlier), the detection limit for cyanide is 8.08 (7.9 + 0.18). Through several iterations, this value was determined to be 0.64 mg/L for sodium cyanide. It has been established that conductivity may be used to provide a good estimate of concentrations of total dissolved solids (TDS) in water (Snoeyink & Jenkins, 1980). The relationship is defined in Eq 1:

$$\text{TDS (mg/L)} = \frac{0.64}{C}$$  \hspace{1cm} (1)

TDS (mg/L) = 0.64\kappa 

in which \( \kappa \) is specific conductance in \( \mu \text{s/cm} \). On the basis of this relation, the detection limit of 5.65 \( \mu \text{s/cm} \) change in conductivity is equivalent to 3.61 mg/L change in TDS. Thus, conductivity provides a detection limit of approximately 3.6 mg/L for any dissolved substances added to the drinking water. With the exception of VX, these chemicals can be detected at concentrations well below those that would be necessary to cause a significant acute hazard to human health.

Animations helped determine placement of detectors. Although various algorithms have been developed to optimize the location of detection equipment in a distribution system (Kessler et al, 1998; Lee & Deininger, 1992), this can also be done using modeling. Contours at various concentrations of toxicological significance were used to map the area of contamination at a particular time (Figure 2). Animations using these snapshots over time were used to show how the contamination travels from a particular point to areas downstream. A visual analysis of animations for different sources of contamination revealed common paths for the transport of contaminants, which became prime candidates for detector sites. The animations also showed where additional contaminant modeling was necessary to verify that a contaminant originating in certain parts of the distribution system would follow these same common paths.

Contamination concentration data versus time at points along the common paths were examined to determine their suitability as detection sites. Criteria for selecting a detection site included the size of the upstream area that could be monitored at the location, the detectability of contamination occurring in this area, and the timeliness of detection. Detectability was greatly affected by mixing, which could reduce the chemical concentration to below the detection limit. Therefore, detection at or downstream of locations where large quantities of water are mixed are not generally suitable for detectors. Four locations were selected and examined together to evaluate the performance of a theoretical system comprised of detectors at these locations (Figure 3). VX was selected to test the detection capability of a detection system composed of these four data points.

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**TABLE 4** Summary statistics for measured drinking water parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Standard deviation</th>
<th>3σ</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine (mg/L)</td>
<td>0.36</td>
<td>0.03</td>
<td>0.10</td>
<td>0.25</td>
<td>0.43</td>
</tr>
<tr>
<td>Conductivity (µS/cm)</td>
<td>106.3</td>
<td>2.0</td>
<td>5.6</td>
<td>103.4</td>
<td>110.9</td>
</tr>
<tr>
<td>pH</td>
<td>7.84</td>
<td>0.06</td>
<td>0.18</td>
<td>7.74</td>
<td>7.99</td>
</tr>
<tr>
<td>TOC (mg/L)</td>
<td>1.91</td>
<td>0.05</td>
<td>0.14</td>
<td>1.81</td>
<td>2.02</td>
</tr>
<tr>
<td>Turbidity (ntu)</td>
<td>0.07</td>
<td>0.02</td>
<td>0.07</td>
<td>0.06</td>
<td>0.73</td>
</tr>
<tr>
<td>Laser Neph (ntu)</td>
<td>0.07</td>
<td>0.05</td>
<td>0.15</td>
<td>0.04</td>
<td>0.95</td>
</tr>
</tbody>
</table>

**TABLE 5** Time of detection by origin of contamination and detector location*

| Contaminant Origin | 
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|-------------------|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2:50 | 3:42 | 1:14 | ND | ND | 6:46 | 4:46 | ND | 2:00 | 6:10 |
| 2 | 3:08 | 2:40 | 1:28 | ND | ND | 1:52 | 3:16 | ND | 2:00 | ND |
| 3 | ND | ND | 1:14 | ND | ND | ND | ND | ND | ND | ND |
| 4 | ND | ND | 2:58 | ND | ND | ND | ND | ND | ND | ND |
| 5 | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| 6 | 2:22 | 3:42 | ND | ND | ND | ND | ND | ND | ND | ND |
| 7 | 1:00 | 3:42 | ND | ND | ND | ND | ND | ND | ND | ND |
| 8 | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| 9 | ND | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| 10 | 4:46 | 9:04 | ND | ND | ND | ND | ND | ND | ND | ND |
| 11 | ND | 2:00 | ND | ND | ND | ND | ND | ND | ND | ND |

ND—not detected
*Time from injection to detection given as h:min; the first detection is shown in bold
†Approximately 40% of the detection limit at 16:10
‡Approximately one half of the detection limit at 10:20
§Approximately one half of the detection limit at 5:30
**Approximately one half of the detection limit at 5:00
RESULTS REVEALED

CONTAMINANT LIMITATIONS

Contaminant feed methodology is hindered by time delay. As discussed earlier in this article, a slowly metered flow of a highly concentrated contaminant was selected as the feed methodology of greatest concern for causing contamination. This scenario produced a delay caused by the time needed to displace the water in the service connection pipe. Depending on the feed rate and the length of the service connection, this time delay could amount to hours before any of the contaminant reaches the distribution system. A high flow of a more diluted contaminant requires the target site to have the capability of storing a large quantity of water, as the backflow through the service connection will not allow for any water to be supplied to the building. It also requires the contaminant to be mixed, which could potentially be harmful or fatal to the saboteurs themselves. The high pressures produced could cause leakage within the building and detectable increases in pressure and flow in the distribution system.

However, this same effect could also be advantageous to saboteurs when distribution system flows are low. The additional water pumped into the system would increase pipe velocity and speed contaminant spread. If the additional volume causes the upstream flow to reverse, a second direction for contaminant spread within the system is opened.

The tank truck/hydrant scenario suffered from the same limitations as the high-flow scenario. This scenario was also limited by the volume of the contaminant solution that can be transported, plus the visibility and pump noise created. The primary problem of the tank truck/hydrant scenario was the necessary speed of this attack. Because the contaminant would be introduced to a flowing stream of water, the volume of water affected by the attack is the product of the flow rates and the length of the injection, as illustrated by Eq 2:

\[ V = \left( Q_{\text{system}} + Q_{\text{contaminant}} \right) t \]  

(2)

If time is limited to several minutes, even at high distribution flows, such as those in 24 in. (600 mm) mains, the volume of water affected is in the thousands of gallons. Given that only 1–2% of drinking water is actually consumed, the effect of this attack is very limited. For example, an attack performed under the cover of night will have much of its contaminated slug used by lawn irrigation systems before morning. Dispersion of the contaminated slug of water, by which mechanism this contaminated quantity could increase, is not considered significant and was therefore neglected by the modeling program (MWH Soft, 2002).

Mixing can produce larger quantities of more dilutely contaminated water. In regard to the highly looped model, the multiple paths allowed the contaminated slug to mix...
with unaffected water. This resulted in multiple slugs passing through many locations in the system (Figure 4) that were frequently diluted but still potentially toxic.

Flow rate, flow patterns, and pipe bifurcation played important roles in contamination. The contaminant feed rate at each location was adjusted to achieve approximately the same initial concentration in the distribution system for each simulation. Using the same feed rate at all locations was not a practical method because the water flow rate in the distribution system varies with location. As discussed earlier in this article, the concentration at the injection site must be limited if a covert attack is intended, and therefore contaminant concentrations high enough to be detectable by the human senses must be avoided. The result was that the flow rate of the water in the distribution system at the point of injection defined the total

*LD*<sub>50</sub>—50% lethal concentration dose; *LD*<sub>Lo</sub>—lethal dose, low
quantity of contaminant that could be injected and was a major limiting factor of the overall effect of the contaminant on the distribution system. The spread of VX from various injection points is shown in Figure 5 as the fraction of the total system demand affected versus time. Contamination originating at locations 1, 2, and 3 had the largest impact on the system. These locations also had the highest flow rates.

Flow patterns and pipe bifurcation also played important roles in determining the extent of contaminant spread. Location 7, although located in the middle of a neighborhood, did not present the same hazard as location 6, which is upstream in the same neighborhood (Figure 1). Location 7 was fairly isolated, and the only nearby bifurcation was located upstream. Location 6 had several branches occurring immediately downstream. The impact of this difference is shown in Figure 6. This result is obvious but only if the flow direction is known, and it illustrates the significance of the hydraulic information that would be needed for a sophisticated and highly effective attack.

Location 1 was on a major supply line, through which the downstream locations received virtually all of their water. Continuous feed of the contaminant eliminated mixing in this region over time, as all downstream flow pathways became contaminated. Because contaminant decay was also minimal, lethal concentrations could be reached even far downstream. This represented the greatest potential danger from contamination.

Effect of contaminant was predictable. All of the chemicals used as contaminants were determined or assumed to be highly persistent. As a result, if all of these contaminants were modeled with the same initial concentration, contamination would result in nearly equal concentrations downstream. Similarly, if an LD₅₀ dose of each chemical was introduced, then the toxicological effect at downstream locations would be virtually the same. Toxicologically equivalent dosage rates were not applied for each of the chemicals used, resulting in differences between the models of each of the four contaminants. Rather, the maximum practical dosage was applied (up to four times LD₅₀ for VX) to illustrate and compare the maximum potential hazard of these chemical contaminants.

The relative effect of these chemicals on the drinking water system was thus predictable, based on the toxicological impact of the initial concentrations. Because VX was introduced at four times its LD₅₀ concentration, it had the greatest lethality. Parathion and cyanide had an extremely limited ability to produce a fatal reaction because of the limit on the dosage that can be practically applied.

Contaminant detection must focus on certain locations. Looking at the concentration-versus-time data at the locations of the four detectors, it was determined that a detection system composed of these four locations would be highly effective for timely detection of these four contaminants originating in most portions of the distribution system. Table 5 lists the times at which contamination was detected at these locations from various points of origin. The first detection is shown in bold.

The results for contamination originating in the lower part of the system (locations 5, 8, and 9), where flow rates and velocity were much lower, show that detection is significantly more difficult because the contamination does not move and spread quickly. At the same time, this lack of mobility also means that the contamination presents a much lower threat. It is not possible to detect the incidence of contamination in every portion of a distribution system. Therefore, contamination-detection system design must focus on the risk incurred by the incidence of contamination in a certain location within the distribution system and how far contamination can spread in significant concentrations.

Contaminant spread from neighborhood to neighborhood. In the process of examining the spread of contamination over time, it was observed that the flow pattern in the distribution system, which determined the spread of contamination, was surprisingly conducive to the transportation of contaminants from neighborhood to neighborhood through much of the system. It had been expected that water would be distributed outward from the grid of 12 in. (300 mm) mains that form the backbone of the supply network. If this were indeed the case, water would only flow into neighborhoods, isolating them from one another.

However, the model illustrated that water actually propagated in sheets that flowed through the neighborhoods, and not just around each neighborhood in the major lines. Once the leading edge of contamination had passed through a neighborhood, the contaminant then flowed into the major distribution lines bordering the neighborhood on its downstream edges. As a result, the 12 in. (300 mm) mains downstream of the neighborhoods acted as major receiving lines rather than as major distributing lines. Thus any occurrence of contamination in a neighborhood would pass from neighborhood to neighborhood. As the contaminant is transported, it would eventually encounter a 12 in. (300 mm) main that would then transport the contaminant—although diluted—to the downstream portions of the network.

CONCLUSIONS REITERATE NEED FOR DISTRIBUTION SYSTEM DEFENSES

The results of the three modeling scenarios show that large-scale contamination of a drinking water system may be accomplished through backflow into major network water supply lines. Strategically located points of attack outside of the major supply lines can also produce large-scale contamination at lesser concentrations. Randomly chosen points for a covert contamination attack within the distribution system will optimally affect an area of a few neighboring streets up to 1 sq mi, depending on pipe velocities and flow patterns within the distribution system, as well as other factors.

The ability to create contamination is based on the flow at the point of injection and the length of time of the
chemical injection. The ability to spread the contaminant depends on pipe velocity as well as flow patterns and pipe bifurcation. Therefore, high-flow locations present a much higher risk to the overall system than other locations. Because each of the four chemicals was modeled as highly persistent, their comparative effects were determined by the toxicity of the highest practical dosage.

A highly successful covert attack on a drinking water distribution system using a continuous feed backflow contamination methodology requires detailed knowledge of system hydraulics. Gross contamination of the distribution system is easily accomplished but could be detectable from taste, odor, or color of the water. Fear could be sown through a community in this fashion, but mass casualties could be avoided through prompt action and public notification. An attack attempt could result in little, if any, effect if the contaminant feed rate is insufficient to create a toxic concentration in the distribution system. For the four chemicals evaluated in this study—parathion, VX, 1080, and cyanide—an order of magnitude in concentration can be the difference between a fatal dose and little or no physiological reaction.

Theoretical calculations indicate that chemical contaminants in toxic concentrations can be detected through the monitoring of standard drinking water parameters for variations from normal conditions. Because of the wide variety of possible toxic contaminants, detection through a broad-spectrum approach such as this may be more beneficial than a focus on individual contaminants. The risk posed by contamination originating in a certain location is generally proportional to the ability to detect it. This is because the risk is represented by the spread of a contaminant, and the greater the spread, the more likely the contaminant will encounter a detector. Contamination that is mobile and presents a significant risk to a large portion of the distribution system can be detected, and this must be the focus of any detection system. Detection by a loose grid of detection points will only occur after a significant portion of the system has been contaminated. Only a highly dense system of detectors will allow both detection and response in sufficient time to control the spread of contamination. Therefore, detection systems should involve rapid consumer notification, for example through reverse-911 calling, to prevent casualties.

Drinking water security must become an issue in the distribution system design process. Access to major distribution lines in distribution networks (i.e., those 12 in. [300 mm] or more in diameter) is of primary concern because of the significantly higher quantity of contaminated water that can be produced at these locations. Distribution system networks should eliminate or minimize the number of service connections and fire hydrants connected directly to these lines, and those that do exist should have backflow prevention devices installed. A risk-based approach to securing distribution system access points of all kinds should be followed. The primary factors for evaluating risk are system flow at the point of access and downstream demand.

ABOUT THE AUTHOR
Timothy P. Allmann is a bioenvironmental engineer at the Air Force Research Laboratory, 2719 12th St., Wright-Patterson AFB, OH 45432; e-mail timothy.allmann@wpafb.af.mil. A member of AWWA, he has 10 years of experience working as a commissioned officer in the US Air Force, specializing in the management of industrial and environmental health hazards. Allmann earned a master’s degree in civil engineering from Colorado State University and a bachelor’s degree in bioengineering from Texas A&M University. Kenneth H. Carlson (to whom correspondence should be addressed) is an associate professor in the department of civil engineering at Colorado State University, Fort Collins, CO 80523; e-mail kcarlson@engr.colostate.edu.

FOOTNOTES
1H2OMap Water, MWH Soft, Inc., Bloomfield, Colo.
REFERENCES


