ENGINEERING REPORT Distribution System Water Quality Modeling

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INTRODUCTION: Public water utilities are tasked with providing safe, reliable water from the source through many miles of pipelines to the customer. Today, water distribution modeling is a critical part of designing and managing these miles of distribution water lines with ever-increasing water quality requirements. In addition, with the threat of terrorism, water purveyors also need tools to predict where their system is most vulnerable and how best to be prepared. Water quality modeling is one of the best ways to prepare prior to making major upgrades.

LITERATURE REVIEW: The literature review for this project consists of the following: understanding chlorine in the distribution system as it affects water quality; determining possible solutions for water quality problems; background on terrorism of water supplies and distribution systems; determining a conservative pollutant to use for analysis; and determining security measures to protect the distribution system.

Chlorine and Its Affect on Water Quality: The use of chlorine began in the early 20th century to prevent water-borne diseases. Before chlorination, filters were discovered which reduced water-borne diseases significantly. In Philadelphia, the rate of typhoid cases dropped from 600 to less than 100 per 100,000 with the introduction of filtration. After the onset of chlorination practices in the 1910's, that number was subsequently reduced to less than 25 in 100,000 (Davis and Cornwell, 2006). In addition to primary disinfection at the treatment plant, water suppliers maintain chlorine disinfection residual in the system (secondary disinfection) to destroy or inactivate microorganisms, as well as for detection of toxic upset to the system and to help prevent microbial growth on the piping in the system. The U.S. Environmental Protection Agency (USEPA) mandates a minimum residual of 0.2 mg/L to enter the system with a "detectable" residual maintained throughout the distribution system (CFR, 2002).

Although chlorination of water has done its job to protect the people from water-borne diseases, it also has its drawbacks. It is toxic in high concentrations and is corrosive. In fact, the USEPA requires that water suppliers limit the maximum residual disinfection level (MRDL) for chlorine to 4 mg/L leaving the treatment plant (CFR, 2002). Chlorine also chemically reacts with naturally-occurring material to form organic and inorganic disinfection by-products (DBPs), which have potential health effects such as increased risk of cancer and organ damage to liver, kidney, or central nervous system (ACS, 2000). The USEPA now regulates the amount of DBPs to a maximum contaminant limit (MCL) of 0.06 mg/L to 0.08 mg/L, depending on the type of DBP (CFR, 2002).

The amount of DBP formation is a function of several factors: type and amount of natural organic matter (NOM) and inorganic constituents, pH, and temperature of the water, as well as type and amount of disinfectant used and contact time. With increase in water age, there is a greater potential for DBP formation and nitrification. Also, higher water temperatures during the summer can increase DBPs as the chemical reactions proceed faster and go further at higher temperatures. Higher water temperatures often cause a higher chlorine demand, which increases the required disinfectant dose and results in higher DBP formation potential. Actually, an increase in any of the factors listed above results in higher DBP formation (ACS, 2000).

Solutions to Chlorination Water Quality Issues: The USEPA has addressed all of the known factors affecting DBP formation in several white-papers and "The Simultaneous Compliance

Guidance Manual for the Long Term 2 and Stage 2 DBP Rules" (USEPA, 2007). These documents address controlling many of the factors through source management or enhanced treatment. Finding sources of water with lower NOM and inorganic constituents, blending with other sources of water, adjusting the pH and/or temperature for enhanced coagulation, and advanced removal processes are all ways of reducing the potential for DBP formation.

In context to reducing DBPs caused by chlorination, alternative disinfectants are recommended. Several alternatives to traditional chlorination exist and are used in many parts of the world, although mostly in developed countries. For water systems with high total organic carbon (TOC), it is recommended that disinfection methods other than free chlorine be used due to the high production of DBPs (USEPA, 2001).

Ozonation is one method used by some water providers in the United States. Due to the fact that ozone does not provide a disinfection residual, secondary disinfection to provide chlorine residual is required by regulation (USEPA, 1999). Ozone is a very reactive disinfectant (more effective than chlorine and chlorine dioxide against viruses, Giardia lamblia, and Cryptosporidium) and does not form chlorinated DBPs. However, it can produce bromide as a DBP, reduce dissolved oxygen levels in the water, form taste and odor problems, and increase corrosion. It also requires additional training for use.

A common alternative secondary disinfectant is chloramine due to its longer half-life in the distribution system, ability to maintain effective protection against pathogens, and lower production of DBPs (USEPA, 1999). Chloramines are formed by the addition of ammonia into the drinking water. The resulting formation has a relatively lower redox potential in comparison to free chlorine, and hence, a lower decay rate. Chloramines can however lead to nitrification in the system, especially under the conditions of: high water age, pH of 7 to 8, high water temperatures of 75° - 85° F, low chloramine residual, and excess ammonia. Chloramines also require a much longer contact time for inactivation of viruses than free chlorine. Therefore, it is typically only used for secondary disinfection. The formation of DBPs will still need to be addressed for primary treatment with this alternative.

UV disinfection is another method which is gaining popularity in the U.S. and used extensively in Europe (USEPA, 1999). It leaves no residue in the water and is effective against Giardia lamblia and Cryptosporidium at low doses. It also does not produce DBPs, and the effectiveness is not dependent on pH or temperature. However, effectiveness of this method is susceptible to power outages and hydraulic upsets. Also, higher doses are needed for virus inactivation, and some substances in water can affect UV disinfection. Also, as with ozonation, it does not provide a disinfection residual in the system and requires additional training for operator use.

Finally, chlorine dioxide is gaining popularity as an alternative disinfection method (USEPA, 1999). Chlorine dioxide effectively inactivates bacteria, viruses, and Giardia cysts and can achieve some Cryptosporidium oocyst inactivation. It produces less DBPs than chlorine, and is also effective as an oxidant to control iron, manganese, hydrogen sulfide, and phenolic compounds. It may treat waters with higher levels of bromide and TOC better than chlorine or ozone, and it is not significantly affected by pH values between 6 and 9. Chlorine dioxide does have a few draw-backs. It forms two types of DBPs (chloride and brominated DBPs); the

MRDL is much lower at 0.8 mg/L than free chlorine; it is less effective at lower temperatures; and has potential odor problems. Other draw-backs are its quick dissipation of residual and additional operator training for use.

The USEPA addresses ways to deal with these disinfectant limitations in their Simultaneous Compliance Guidance Manual (USEPA, 2007). Consideration must be given to the water quality issues of the water supply to determine which disinfection method (or combination) is best to meet the regulations.

An important discussion regarding water quality involves solutions that can be managed in the distribution system itself. Physical and operational changes to the distribution system can improve many water quality issues. These changes can lead to removal of sediments in the system, wasting or reduction of bacteria, organic and inorganic matter, DBPs, and reduction in water age.

High water age is typically a result of development of water storage and distribution systems to meet future water demand and fire flow requirements. This in itself can create water storage requirements of multiples higher than daily use. Solutions to decrease water age and improve water quality may include: improving water circulation, pressure, and velocity, eliminating deadends, opening valves, uni-directional flushing plans for low use areas, and increasing turnover rate in storage facilities (Singleton, 2007).

Locating and correcting the water quality problems in the water distribution system requires time-consuming and sometimes expensive sampling and lab analysis, flushing plans, and operational techniques. To minimize the work required, water quality modeling has become an increasingly popular initial step. Water quality models are direct extensions of hydraulic network models of distribution systems by addition of physical and chemical processes of transport, mixing, and decay. By modeling transport of disinfectants or contaminants (such as DBPs) through pipes, mixing at nodes and in water storage tanks, and decay of the constituent itself through an extended period simulation, predictions of water quality problems and effective solutions can be obtained (Haestad Methods, 2003).

Terrorism in Water Supplies and Distribution Systems: Threats to drinking water systems have long plagued human history, but public concern of these threats peaked after the terrorist disaster of September 11, 2001 (McGraw-Hill, 2004). Since that time, public water systems have implemented security measures to prevent contamination of the water supplies. In fact, the U.S. government has mandated that security be addressed by passage of the Public Health, Security and Bioterrorism Preparedness and Response Act (Bioterrorism Act). Every community water system that serves more than 3,300 people must conduct a vulnerability assessment and prepare an emergency response plan for the water system (USEPA, 2002a).

The threats to water systems have been characterized as four types: cyber threats, physical threats, chemical threats, or biological threats. Cyber threats consist of electronic attacks such as disruption, viruses, or jamming of the control system to cause failures or misrepresentation of the data being collected. Interferences such as these can lead to over- or under-dosing of chemicals due to the misrepresentation of actual amounts being recorded (McGraw-Hill, 2004).

Physical threats consist of any physical destruction to the infrastructure. This may include major terrorist activity such as bombing parts of the system, but can also be as simple as rapid opening and closing of valves to cause water hammer effects to result in main breaks. Loss of pressure in the system can result in bacterial contamination of the water supplies by backflow and result in reduction of fire fighting capabilities (McGraw-Hill, 2004).

Chemical and biological threats consist of chemical warfare agents, industrial chemical poisons, and pathogens and biotoxins - most of which are resistant to disinfection by chlorination. Pathogens such as Giardia lamblia and Cryptosporidium parvum have been known to cause widespread illnesses (even deaths) in water supplies, while cholera and typhoid are still major killers in parts of the world. The chemical warfare agents are primarily classified by their damage: nerve, blister, or choking, as well as those that enter the blood stream and hallucinogens. Industrial poisons consist of insecticides, solvents, corrosives, caustics, and heavy metals. The concentrations of some effective chemicals, including chemical warfare agents and industrial chemical poisons, that can cause immediate death or debilitation (acute concentrations) range from 50 μ g/L to 5000 mg/L in 0.5 L of drinking water (McGraw-Hill, 2004).

The effects of chemical and biological contaminants in water supplies are numerous. They include:

- the primary concern of health issues (illness or death) to the consuming public
- economic impacts to the public utility
 - o inability to sell contaminated water
 - o expenses to decontaminate water before release into the environment
 - flushing, cleaning, and replacing water in the distribution system
- economic impacts to customers, especially businesses, with the inability to use contaminated water or the required time and effort to take decontamination measures before use

• legal impacts to the public utility due to damage or health impacts from the contaminated water

• loss of confidence by the public

- \circ in the utility's ability to deliver safe water, possibly resulting in increased public health impact as users may seek other, perhaps unsafe, water supply sources
- o criticism in the corporate audit process (ASCE, AWWA, and WEF, 2004a)
- disruption of vital services, such as water for fire protection and medical facility needs (USGAO, 2003)

In addressing vulnerability to water systems, it has been noted that the distribution system is considered one of the most vulnerable parts, according to a study by the U.S. General Accounting Office (USGAO, 2003). There are many ways in which contaminants can purposefully, or accidentally, enter the distribution system. They can be dumped in water storage tanks, injected into pressure pipes through a bleeder valve, or forced into the system from any tap or fire hydrant. Accidental contamination can occur through spills into source waters (such as a boat spill on a navigable waterway, wastewater effluent discharge, or non-point source runoff upstream of water supplies) or from backflow of contaminants due to pipe breaks or

repairs. The most vulnerable sites for intentional contamination include: reservoirs and storage tanks, pumps, valves, fire hydrants, and customer taps. (ASCE, AWWA, and WEF, 2004a).

Analyzing the vulnerability of water distribution systems includes identifying the salient characteristics of a contamination scenario. These characteristics include: a) the contaminant species; b) the amount inserted; c) the location of the insertion, and d) the rate and/or method of insertion. As the contaminant is inserted, it produces a "pulse" with a particular duration and concentration profile dependent on the scenario and properties of the water system. The key feature of a successful vulnerability analysis, then, is to identify potential contaminants and toxic doses, identify specific vulnerable sites, and model the effects of potential doses and methods of insertion at the various vulnerable sites (ASCE, AWWA, and WEF, 2004a).

Determination of Conservative Pollutant: There are many features of pollutants that present likelihood for use by a terrorist. The ideal contaminant may have the following features: availability, lethality, potency, and persistence in water (Allman, 2003). The pollutant should be available for purchase or able to manufacture by a skilled person. The pollutant should be deadly at a low dosage, and should last for extended periods. The low dosage is considered for ease in undetected contamination by minimizing the amount to be injected or dumped, as well as minimization of taste, sight, or smell detection. Finally, a low decay constant is necessary to ensure persistency of the lethal dose to reach the tap, which then allows the contaminant to be modeled as conservative (non-reactive) pollutant.

Potential pollutants that meet these criteria are: parathion, a highly toxic insecticide (now banned in some countries, including the U.S.) with low pale-yellow and faint garlic odor and low decay rate; VX, odorless, pale-yellow highly toxic nerve agent (banned by international treaty) believed capable of being manufactured by skilled individuals with low decay rate; sodium monofluoroacetate, an odorless, tasteless rodenticide currently in use in many countries (including limited use in the U.S.) with a very low decay rate; and cyanide, available in many toxic forms, and expected (not known) to have a low decay rate. Sodium monofluoroacetate is believed to be very stable in water with chlorine, whereas the others react but produce highly toxic products with these reactions (Allman, 2003).

The chemical pollutant chosen for this study is VX. VX meets the above criteria, is viscous, non-volatile, and has a very low 1_{st} order decay constant (3.77 X 10-3 hr-1at pH of 8 and 25_oC). Its acute concentration in 0.5 L of water is 50 µg/L, which indicates a low dosage for lethal or debilitating effects. Also, it has previously been determined to produce the greatest and most deadly spread of contamination of the pollutants described here (Allman, 2003). Table 1 below

Table 1 - Chemical Pollutant Concentration and Feed

Chemical	Acute Concentration-AC	Feed Condition	Feed Rate for	Volume of VX in
Agent	(µg/L in 0.5 L drinking		Injection at Housing	28.5Kgal
	water)			Clearwell
VX	50	100 mg/L	15 gpm @ 80 psi	2.85 gal pure

defines the characteristics obtained for analysis in this project (Allman, 2003 and McGraw-Hill, 2004).

Security Measures to Protect Water System: Many organizations have developed guidance documents and tools for characterizing the vulnerability of a water system. The American Society of Civil Engineers, American Water Works Association, and Water Environment Federation collaborated efforts to develop a set of guidelines for addressing the physical security of water and wastewater systems, as well as guidelines for an Online Contaminant Monitoring System (ASCE, AWWA, WEF, 2004a). USEPA developed a Response Protocol Toolbox for dealing with contamination threats and incidents to water systems (USEPA, 2003). Water Information System and Analysis Center (WaterISAC) was developed to provide a secure webbased resource for water and wastewater utilities to receive early warnings of potential threats as well as obtain information about water system security (WaterISAC, 2008). Other available tools and guidance documents are discussed in *Water Supply Systems Security* (McGraw-Hill, 2004).

The security measures discussed here will center on the distribution system, which is considered one of the most vulnerable parts of the system (USGAO, 2003). Security measures for the distribution system consist of the following groupings: control of the physical features of the system, monitoring and modeling of the distribution system, and an emergency response plan (Haestad Methods, 2003). Physical monitoring of the infrastructure, such as security cameras placed throughout the distribution system, may be a good way to prevent terrorism, but is not considered cost-effective. It will not be addressed here.

The physical features (or infrastructure) of the water distribution system consist primarily of booster pumping stations, water tanks, fire hydrants, valves, and SCADA controls to feed back to a central office. Security measures to protect from physical or cyber threats to this system include: redundant systems, operational backups, backup power systems, and fencing around aboveground structures (ASCE, AWWA, WEF, 2004b). Water Quality Modeling – CIVE 695G – Antonia Ortiz – 6/20/08 Page 9 of 66

To prevent chemical and biological contamination, this infrastructure should be regulated. A policy should be in place to regulate the use of fire hydrants for authorized use only. Fire hydrants should be designated and documented for use by the public (such as for construction activities), and these hydrants should have backflow prevention devices installed. All other exposed entry points should be locked, fenced, and have backflow prevention devices (Haestad Methods, 2003).

Because these solutions can be costly and are not infallible, active monitoring and modeling, and an emergency response plan are paramount to prevent terrorism (McGraw-Hill, 2004, Haestad Methods, 2003, and ASCE, AWWA, and WEF, 2004a). Water providers are required by USEPA to monitor the water quality of their system in regards to chlorine, DBPs, and other naturally-occurring water contaminants. However, to be effective, security in the water system needs to offer real-time monitoring at selected points throughout the water system with sensors to detect and measure changes in water quality. Modeling helps the provider to understand the hydraulics of the system for developing monitoring systems and responses, to determine most effective locations for the sensors, as well as to track contamination back to its source (postterrorism modeling). It provides a means to predict concentration and spread of contaminant for better use in monitoring and response (Haestad Methods, 2003). To adequately utilize modeling and monitoring, initial information is needed. As discussed above, the credible threat agents must be identified and prioritized, the dosages and behaviors of the agents must be understood, and the points in the system that are vulnerable to contamination must be determined. Many lists have been developed on potential agents (USEPA, 2003). The characteristics of the prioritized agents are also available to allow a utility to model the outcome of contamination in their system. Each utility must assess the vulnerable points in the system, such as those listed as physical features of the distribution system (ASCE, AWWA, and WEF, 2004a).

Monitoring consists of sensors placed at strategic locations in the system to determine baseline as well as changes in water quality. Studies have been conducted to determine appropriate sensors for use with various pollutants. Some of the sensors studied include: chlorine, UV254, conductivity, pH, turbidity, or combination units. Testing at Colorado State University (CSU) of ten potential contaminants provided results for these sensors on the specific (considered high priority) pollutants (Byer and Carlson, 2005, and Cho, 2007). The results indicated that chlorine or pH alone were not good analyzers of water quality changes for these pollutants (negative responses for 4 or 5 of the 10), but UV 254, turbidity, conductivity, and the suite of sensors (turbidity, chlorine and pH) provided positive results for 8 or 9 of the 10 contaminants. Hach has developed a combined monitoring system called GuardianBlue Security System that is the first and only early warning system for drinking water to earn the SAFETY Act designation and certification from the Department of Homeland Security. This system continuously monitors (with baseline comparison every 60 seconds) the turbidity, pH, conductivity, chlorine, pressure, and temperature (Hach, 2008).

The next step for developing security measures for the distribution system consists of developing possible responses to a contamination threat. An emergency response plan is paramount for protecting the water users. An initial response to a contamination threat consists of notifying the authorities and the public and providing an alternate supply of water (or boil notice, if appropriate). Characterizing and locating the contaminant should be the initial step in solving the problem. Sampling the distribution system, preferably with use of an online monitoring system, and modeling the source of the contamination is important for determining this information. Finally, remediation (e.g. purging the system of the contaminant by valving and flushing, and re-testing to confirm removal of the contaminant) should follow (USEPA, 2003). Decontamination of the affected water is likely required before discharge to the environment.

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