Distribution Systems: The Next Frontier

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Drinking water treatment technology has advanced significantly over the past century. However, once the highly treated water leaves the treatment plant, it must travel to consumers through a distribution system. A variety of opportunities exist in the distribution to degrade water quality and affect the end product consumed by the public. As the last barrier in the treatment process, distribution systems are a vital to the protection of public health. Because pipes are buried and outside of the direct control of water utilities, managing distribution systems is one of the greatest challenges in the provision of safe drinking water.

Within the past few decades, an increasing focus of research has been placed on distribution systems. It is a difficult balancing act to maintain continuous water supply to customers, provide adequate fire flow at all parts of the system, maintain pressure, and ensure water quality. Distribution systems are built as cities grow and therefore contain a variety of pipe ages, materials, and quality of construction. Many systems contain pipes that are over 100 years old, most of those constructed of unlined cast iron. Replacement costs are rising, with estimated costs of replacing water system infrastructure in the U.S. ranging from $77 to $325 billion in the next 25 years (Deb et al, 2002). Increasing energy costs are also adversely affecting water utilities who rely on extensive pumping to maintain pressure and deliver water.

The National Academy of Sciences recently convened a panel to examine public health risks from distribution systems (NRC, 2007). This report focused on three areas related to distribution system integrity: physical, referring to the pipes as barriers; hydraulic, referring to the delivery of water at the desired quantity and pressure; and quality, referring to the maintenance of the water quality through its travel in the distribution system. All three areas of integrity must be addressed to ensure public health. High priority areas for risk reduction identified by the panel included cross-connections, new and repaired water mains, and water storage (NRC, 2005).

Distribution systems represent the next frontier of research needs and technology challenges for the drinking water industry. In addition to the infrastructure replacement and management challenges, water quality issues are highly scrutinized by the public and media. Tools are emerging to address these challenges but considerable work remains to fully address the issues.

DISTRIBUTION SYSTEM WATER QUALITY

One key to the protection of public health in the distribution system is the maintenance of a disinfectant residual, typically in the form of free chlorine or chloramine. As water travels through the distribution system, the disinfectant oxidizes material in both the bulk water and at the pipe wall surface, thereby reducing the residual available to maintain disinfection (Figure 1). At the pipe wall, the chlorine can react with corrosion products, sediments, and biofilms. Biofilms have been shown to be able to grow on most common pipe materials but the quantity of attached bacteria is several orders of magnitude higher on unlined cast iron pipes (Camper et al., 2003).

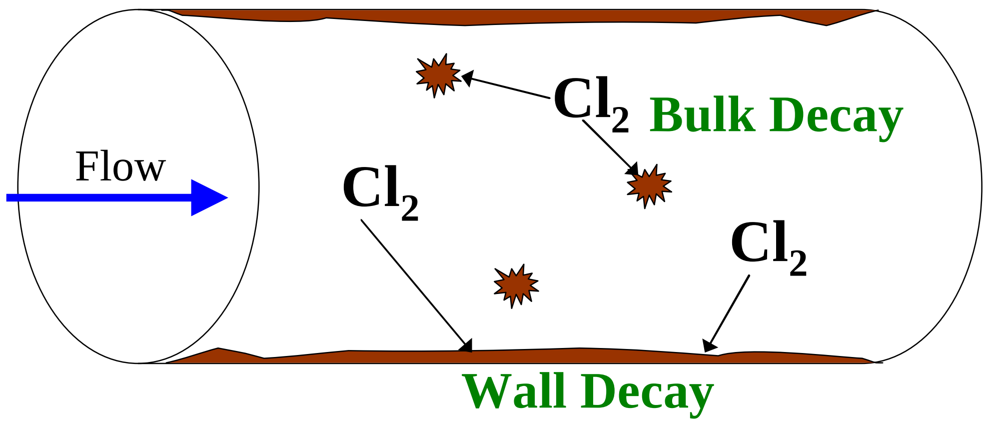

Figure 1. Schematic of Chlorine Decay Reactions in a Distribution System

Drinking water regulations place limits on the minimum and maximum amounts of disinfectant allowable in the water. In addition, several classes of disinfection by-products are regulated. These compounds, which form when chlorine reacts with natural organic matter present in the water, are suspected carcinogens and have potential reproductive health effects (USEPA, 2006). They continue to form in the presence of free chlorine as water travels to the consumer. Therefore it is important to deliver the treated water as quickly as possible to the end users to reduce the potential for disinfection by-products to form.

Microbial contamination in the distribution system is also a potential threat to public health (Craun and Calderon, 2001). Pathways for entry of microbial contaminants into the distribution system include survival of organisms in the treatment process, intrusion of contaminated ground water from the outside of the pipe when pressure drops within the pipe, contamination during main installation or repair, or backflow from a non-potable system connected to potable plumbing. The presence of pathogens within the biofilms or entering the distribution system is not well understood and considerable research is needed to fully understand the microbial interactions taking place throughout the system.

Storage of water is provided in elevated tanks, ground tanks, and sometimes in the pipes themselves. Depending on its design and operation, there is potential for water to remain within the tank for extended periods of time. The longer the retention time in the tank, the greater the potential for residual disinfectant decay, formation of disinfection by-products, and microbial regrowth. Therefore management of storage is a critical issue for distribution system operation. Furthermore, the need for fire flow storage often results in design of larger tanks than would be optimal for water quality purposes. The design and operation of storage varies widely across the country, with regional preferences and architectural influences playing a large role. Tanks have also been shown to be the site of contaminant entry into the distribution system, either through broken hatches or sediment accumulation (Clark et al, 1996).

The distribution system is connected to every location where water is available to consumers. Typically, the water utility’s jurisdiction ends at the customer’s meter and the remaining plumbing is the responsibility of the building owner. All the reactions which can degrade water quality in a distribution system can occur within household plumbing. Many incidents that gain media attention are linked to household plumbing issues, such as the problems with lead in Washington DC in 2004 (USEPA, 2007). Intentional contamination of the system is also a potential threat.

TOOLS TO ADDRESS DISTRIBUTION SYSTEM ISSUES

Because access to the distribution system itself is extremely limited, the water industry relies on a variety of tools to operate, maintain, and continually improve these systems. A variety of water quality sampling is conducted daily to meet regulations and to inform decisions about operations. While collection of grab samples has been the traditional sampling method, the use of online monitors is increasing. These monitors can include measurement of simple water quality parameters like pH and turbidity as well as more sophisticated analyses such as total organic carbon. Considerable research is ongoing to determine the optimal number of grab samples and online monitors and their placement, the best parameters to monitor for different objectives, and most accurate analytical methods (Speight et al, 2004). Along with the collection of online water quality data, a field of work is emerging in data analysis and event detection (Hart et al, 2007). While much of this work originated in the security arena, water utilities are seeking multiple benefits from this expensive equipment and are looking for basic operational information as well as indication of a contamination event, intentional or otherwise (ASCE, 2004).

Hydraulic and water quality modeling tools provide a way to link hydraulic and water quality parameters in a simulation. Hydraulic models have been in use for several decades and can provide reliable simulations of flows and pressures when appropriately calibrated to real-world conditions (Ormsbee and Lingireddy, 1997). Figure 2 shows the input data required for hydraulic and water quality models using chlorine modeling as an example.

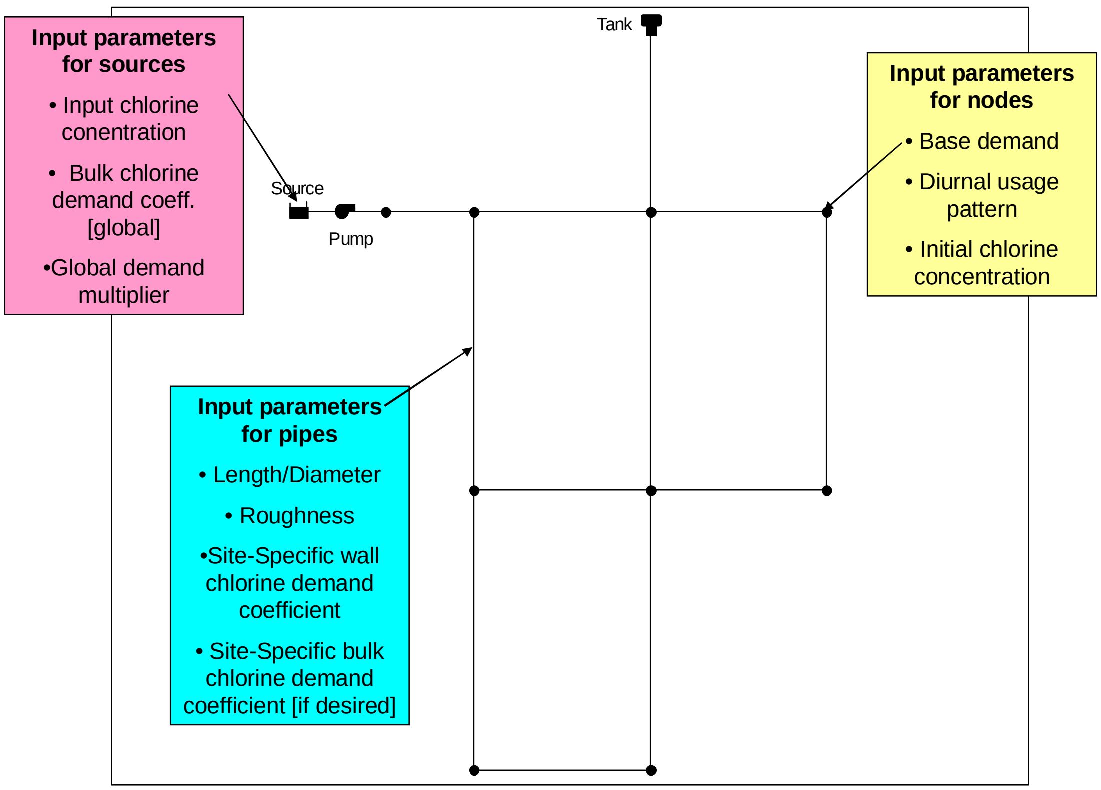

Figure 2. Schematic of model input requirements to simulate chlorine in a distribution system.

A key challenge in hydraulic modeling is the determination of customer water usage at all points in the distribution system over time. Where customer meters exist, they are generally read on a monthly or quarterly basis and do not provide real-time data.

Innovations in automated meter reading (AMR) may improve our ability to collect real-time customer usage data but the data management challenges are significant. Very few utilities have implemented "real-time" modeling of their distribution systems by linking operational data with the model and running repeated simulations. Real-time models are primarily used for detection of situations that differ from baseline, such as main breaks or large fires, as well as energy management (Jentgen et al, 2003). The field has not yet advanced to the level of sophistication needed to fully automate the operation of a distribution system using a real-time model.

Water quality modeling is still considered an emerging field but is increasingly used to assist in operational decisions and planning studies. Chlorine is the most commonly modeled parameter for water quality. A relatively simple first-order decay model for chlorine has been shown to provide good simulations of field data (Vasconcelos et al., 1997). Modeling of disinfection by-products has been less successful using deterministic models (Speight et al, 2000). Probabilistic models of water quality hold some promise in that they allow the use of uncertain mechanistic formulations with appropriate accounting of uncertainty.

Modeling of microbial contaminants within the distribution system is limited by the lack of knowledge about biofilm processes, attachment/detachment of microbes to particles, growth mechanisms in low nutrient environments, concentrations of microbes that enter the system through different pathways (e.g. low pressure transient versus cross connection with a sewer), and occurrence of pathogens. Particle transport and deposition modeling is particularly challenging for distribution systems because of the highly variable nature of flow, which in turn is caused by the highly variable nature of individual water usage.

The asset management field is developing tools to model infrastructure deterioration based on data input such as pipe age, material, soil conditions, and number of breaks. The development of reliable, in-situ condition assessment technologies for water mains is an emerging field as is the development of methods for quick rehabilitation that limit the time a water main is out of service. Given the large financial burden of replacing the deteriorating water distribution infrastructure in the U.S., cost-effective approaches to asset management, rehabilitation and replacement will be needed.

Alternative water delivery systems are also emerging, including dual distribution systems carrying potable water and non-potable water separately. In certain parts of the county where water supply is scarce such as Florida and California, the use of reclaimed water (highly treated wastewater effluent) is commonplace and dual distribution systems are being installed throughout cities to provide an alternative for irrigation and fire fighting needs. The challenges associated with potable water distribution systems exist in parallel for reclaimed water distribution systems and include maintenance of the integrity of the buried infrastructure, maintenance of water quality, and delivery of adequate supply and pressure. Point of use treatment devices are also being considered in areas where achieving the desired water quality at the consumers tap is not achievable.

CONCLUSIONS

Water distribution systems represent an exciting challenge for the engineering community. Solving the distribution system problems will require work in a variety of inter-related fields including infrastructure materials, water treatment, hydraulics, water chemistry and microbiology, data management, computer modeling, human behavior, public health and public education, and risk management.

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FURTHER READING

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USEPA, Total Coliform Rule Issue Papers, http://www.epa.gov/safewater/disinfection/tcr/regulation_revisions.html