

Modeling Water Quality in Distribution Systems

Second Edition
Robert M. Clark



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Robert M. Clark**



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Dedication

To my supportive and understanding family, especially my grandchildren, Thomas, Nicholas, Benjamin, and Eleanor. They have helped me to appreciate and understand the real meaning of life.

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Preface

When I initiated USEPA's research studies in an attempt to understand the factors that influence water quality in drinking water distribution systems, I had no way of anticipating how the studies would eventually impact our field. While my colleagues and I were pursuing this research, we were frequently warned that our efforts were a waste of time and resources and were told repeatedly that drinking water networks were much too complicated to lend themselves to systematic scientific study, let alone be amenable to predictive modeling. Nevertheless, we committed ourselves to conducting carefully constructed field studies as the basis for developing and validating our hydraulic/water quality models, and to developing models on a logical, incremental basis.

As our work progressed, it became obvious that drinking water distribution systems were much more dynamic than we originally thought, and we moved from the development of steady-state models to dynamic models. An important principle that developed from our research was the need to be meticulous in developing properly calibrated hydraulic models to provide the basis for our water quality predictions. The progress of this research is discussed in chapter 8.

A problem we encountered early in our work was the large amount of data being generated from our network analysis. Because of limitations in available software, we were forced to run our hydraulic and water quality models separately, but it became clear that we needed to integrate these two aspects of our efforts. As a result, EPANET was developed to provide this increased efficiency. The immediate, widespread response to the availability of this tool was phenomenal. Two decisions that I believe eventually shaped the future of hydraulic/water quality modeling and its applications were the decision to make EPANET a totally public sector model and the decision not to provide technical support for its implementation.

At one point, we contemplated a licensing arrangement with AWWA and distributing EPANET in a manner similar to some of the software developed by other agencies of the federal government. However, we decided not to follow that path but to make EPANET freely available in the public sector. Consequently, it has become widely used throughout the world and has also become the basis for many proprietary models. The decision not to provide technical support for EPANET, I believe, provided the basis for the development and application of many of the proprietary models in use today. In addition to the development of many proprietary models, a large number of

special-purpose modifications have been made to EPANET, primarily by academics. As discussed in chapter 10, USEPA is planning to eliminate all of its technical and development support for EPANET. This is most likely because the EPANET code is widely available and easy to modify, and the original code and many modifications can be obtained from various sources with minimal effort.

As discussed in chapter 12, water quality modeling is an extremely powerful tool for analyzing the fate and effect of contaminant transport in drinking water distribution systems. However, it is important for modeling practitioners and decision makers to recognize that modeling has limitations and that models are only representations of reality, not reality itself. This caution is repeated throughout the book. It has been, however, highly gratifying to see that hydraulic/water quality modeling tools have progressed from being a curiosity, as they were when we started our work, to the situation today in which they have become widely accepted and incorporated as a routine tool for application in our field. I hope this book helps contribute to and continue this progress.

This second edition extends and expands the first edition and addresses the many developments that have taken place in the field over the last 14 years.

Chapter 1 discusses the general characteristics of water supply in the United States. It addresses issues related to water scarcity, water security, the effects of climate change, and the general organization of water supplies in the United States. It also reviews the technical elements common to most US water supplies and discusses basic design and operational philosophies that are predominant in the industry.

Chapter 2 reviews public health and regulatory issues related to water supply. This chapter discusses the distribution system as a barrier to waterborne disease, water quality deterioration in distribution systems, the Safe Drinking Water Act, and recent recommendations from the National Research Council related to drinking water distribution systems.

Chapter 3 addresses the fundamentals of water quality modeling and monitoring in drinking water distribution systems. Various types of distribution system models are discussed, and issues such as the importance of adequate hydraulic representation and model calibration are reviewed. The important interactions between water quality modeling and monitoring are highlighted, and current commercial water quality models are discussed.

Chapter 4 discusses typical chemical and microbiological contaminants found in drinking water and the integration of modeling and monitoring. Important issues include the following monitoring issues: regulatory monitoring, security, process control, routine and compliance monitoring, automated/online monitoring, monitoring equipment, establishing requirements, monitoring parameters, number and location of monitors, monitoring characteristics, amenability to remote monitoring and SCADA integration, and online sampling/control devices. Several monitoring case studies are presented.

Chapter 5 reviews the important hydraulic principles that underlie water quality modeling. In addition, the chapter discusses the application of hydraulic models, including modeling temporal variations in systems, model calibration, fire-flow issues, and flushing water mains.

Chapter 6 provides an overview of fundamental water quality principles. EPANET as well as other water quality models are reviewed, and commercial hydraulic water quality software is discussed.

Chapter 7 presents various models that predict disinfectant decay and the formation of trihalomethanes. Exposure modeling is also discussed.

Chapter 8 provides an overview of some of the first water quality modeling studies in the United States, including studies conducted in collaboration with the North Penn Water Authority, the South Central Connecticut Regional Water Authority, and the North Marin Water District. Results from an important study, conducted by the American Water Works Association Research Foundation (now Water Research Foundation) in collaboration with the USEPA, are presented.

Chapter 9 presents several case studies in which water quality modeling has played a critical role. They range from waterborne outbreak studies conducted in Cabool and Gideon, Mo., and in Walkerton, Ont., to chronic-exposure examples as demonstrated in Dover Township, N.J., and Camp Lejeune, N.C. The use of water quality modeling to assess the vulnerability of a utility to security threats is illustrated by a case study conducted by East Bay MUD in California.

Chapter 10 addresses advanced concepts in water quality modeling. These concepts include the application of geospatial tools, the integration of geographic information systems and water quality modeling, multispecies modeling, distribution systems security, water quality and pressure transients, current USEPA research activities, and several newly emerging research areas.

Chapter 11 provides guidelines on how to get started in modeling and in planning and designing a water quality simulation study. The topics covered include the need to define the scope and the problem definition associated with a modeling study. Issues addressed include: model selection and setup, network representation, calibration/validation model application analysis and display of data, and typical model applications.

Chapter 12 is intended to remind practitioners of some of the limitations associated with water quality modeling. To illustrate these cautions, the inconsistencies regarding our understanding of the nature of bulk and wall reactions associated with chlorine decay are discussed.

Appendix A provides an in-depth discussion of the potential associated with the calibration and validation of models using tracer techniques. Appendix B contains several example applications of EPANET. Appendix C reviews the very important and frequently unappreciated aspect of water quality modeling associated with proper tank design and operation. Appendix D contains typical conversion factors that apply to water quality modeling, and Appendix E contains color figures that support the previous chapters and appendices.

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Chapter 1

Characteristics of US Water Supply Systems

Introduction

The quest for pure water is well documented even in earliest times. One of the earliest recorded works on medicine advises “to heat foul water by boiling and exposing to sunlight and by dipping seven times into it a piece of hot copper and then to filter and cool in an earthen vessel. This direction is given by the god who is the incarnation of medical science.” This statement is attributed to the “Naghrund Bhuson,” a collection of medical maxims from the *Ayura Veda*, the earliest known Sanskrit work on medicine (Baker 1949). Many references are made to the need to acquire and purify water throughout history. The earliest known apparatus for obtaining clarified liquids was pictured on Egyptian walls in the fifteenth and thirteenth centuries BCE. In the Bible, Moses is said to have sweetened bitter waters by casting them into a tree shown him by the Lord. During his forty years wandering in the wilderness, Moses is said to have brought forth water by smiting a rock (Baker 1949).

The Romans demonstrated the importance of an adequate water supply to the development of organized cities and communities. Vitruvius (84 BCE) discussed the various elements of water supply in Book VIII of *De Architectura* including a source of information on springs and the uses and quality of water. One of the most famous water engineers in history was Sextus Julius Frontinus (AD 40–103), the water commissioner of Rome, who in AD 97 wrote a two-volume treatise describing the Roman water system. Frontinus declared that the Roman aqueducts were the real mark of civilization and wrote of settling reservoirs at the head of one of the aqueducts supplying Rome and of pebble catchers built into most of the aqueducts. As with water systems in modern times, the Roman water systems were constructed to support a number of uses, such as supplying water for the public baths and fountains, and not solely for drinking water (Mays 2002).

In the United States, one of the first water systems was built in 1754 by the Moravian settlement in Bethlehem, Pa. It consisted of spring water forced by a pump through bored logs. The city of Philadelphia was also developing a water system at that time. Cast iron has been the material used by most older cities in the United States since its introduction in the early 1800s. The first cast-iron main was laid in Philadelphia in 1817. In 1948, ductile-iron pipe, which has the favorable characteristics of both steel and cast iron, was invented. Boston started using ductile iron in 1968 and has used it exclusively since 1970

(Mays 2000). The estimated 980,000 mi (1.6×10^6 km) of water mains in the United States are being replaced at an estimated rate of once every 200 years (Grigg 2005).

A large range in type and age of pipes makes up today's water distribution systems. The oldest cast-iron pipes from the late nineteenth century typically have an average useful life-span of about 120 years because of the pipe wall thickness (AWWA 2001, AWWSC 2002). In the 1920s, the manufacture of iron pipes changed to improve pipe strength but with a thinner wall and an average life of about 100 years. Pipe manufacturing continued to evolve in the 1950s and 1960s with the introduction of ductile-iron pipe. Polyvinyl chloride (PVC) pipes were introduced in the 1970s and high-density polyethylene in the 1990s, both of which are very resistant to corrosion but with lower strength than ductile iron.

Water quality can be enhanced by source water protection and by treatment, including disinfection. Some pathogens have a relatively short life in water and will not survive storage for even a few days. Filtration will remove bacteria, cysts, and larger particles, but viruses will pass through the filter. Also, the filters need to be cleaned or replaced regularly so that they do not become a source of pollution themselves. Chlorination is probably the most effective disinfectant and should be maintained at 0.2–0.5 mg/L of water. Water can be boiled in an emergency to eliminate pathogens, and municipalities may issue orders to households to boil water when pathogens enter the water supply.

In the United States and throughout the world, drinking water utilities face the challenge of providing potable water to their consumers. However, many factors can result in the degradation of water quality before it is delivered to the customers. For example, treated water may be transmitted through a network of corroded or deteriorated pipes.

Water Scarcity Issues

It is estimated that for the period 1990–2025 there will be water scarcity problems in 118 countries. Approximately 1 billion people face absolute water scarcity because they live in arid regions that lack sufficient water resources. Another 348 million people face severe water scarcity because they live in regions where existing water resources require high-cost water-acquisition developments such as dams, wells, reservoirs, and aqueducts to tap their potential (Bruins 2000).

Global water use has more than tripled since 1950 mainly based on the availability of surface water resources such as rivers, lakes, and groundwater. Water use is generally categorized as follows:

- Domestic or urban water use
- Agricultural water use
- Industrial water use

Irrigation is the largest consumer of freshwater, using over 70 percent of all developed water supplies in the world. Most often, increasing water demands are met by large engineering projects that involve building dams and storing surface water. Some very large surface water projects include the Sardar Sarovar Dam in India and the Three Gorges Project in China. The number of large dams in the world increased from 5,000 in 1950 to about 38,000 by 1995. There has also been increased drilling of groundwater wells. For example, in India the area irrigated from groundwater is greater than all other surface water irrigation combined. Throughout the world, groundwater resources are being overutilized. For example, in northern China, groundwater tables are declining

at approximately 1 m (3.28 ft) each year; in the Punjab region of India, groundwater tables are declining 20 cm (7.87 in.) each year. Rivers and lakes will eventually dry up as groundwater disappears (Bruins 2000).

The United States is generally blessed with adequate water resources. The contiguous United States receives an average of approximately 75 cm (30 in.) of rainfall per year, although a great deal of variability is found across the country (Clark and Sethi 2002). The Northwestern part of the United States has the most rainy days in the contiguous United States, while the Southwestern United States has the fewest (NRC 1999). However, the Southwest often receives great amounts of precipitation over a short period of time, while the Northeast has more precipitation in smaller amounts over a longer period of time. Evaporation is important to water supply because it represents the natural loss of otherwise available water. Annual average values of evaporation range from 50 cm (20 in.) in northern Maine to 215 cm (86 in.) in southwestern California.

Representative soil water budgets for the United States show that the magnitude of surpluses and deficits varies greatly by region and season. The largest deficits occur in the Southwest, while the greatest surpluses occur in the Pacific Northwest and the East. The average annual runoff for the contiguous United States is approximately 30 cm (12 in.) but varies widely. The rates range from less than 0.6 cm (0.25 in.) in some Western areas to more than 50 cm (20 in.) in some parts of the East. Year-to-year variations in precipitation and runoff can also be significant. Changes may occur over a span of decades or centuries, and climatologists have only begun to understand how large an impact these changes might have on local and regional weather patterns (NRC 1999).

Ninety-seven percent of all freshwater on earth is groundwater and only two percent of freshwater is contained in lakes and rivers. The United States obtains at least 23 percent of its domestic and industrial water supply from local and regional aquifers, many of which are restored at rates often less than 0.2 percent per year by volume. Almost all rural homes and many cities depend heavily on groundwater. Throughout the West and Midwest, large aquifers have declined substantially because extraction rates have exceeded recharge rates (NRC 1999).

Significant spatial differences often separate areas of high water demand from areas of water surplus, and therefore water transfers play an important role in the United States. Between 1935 and 1965, water storage in western US reservoirs increased from about 5 million acre-ft to 270 million acre-ft (6.2 billion–332.9 billion m³). For example, the Colorado River is fed from the mountains and once flowed through the deserts of the Southwest and emptied into the Gulf of California. By compact the entire flow was apportioned to seven states, including California, Nevada, and Arizona, and the river's water has been transported to regions outside the river's watershed. Because of erroneous long-term stream flow measurements, more water was apportioned than would normally be available. A series of reservoirs made the water readily available for consumption, so that little flow now reaches the ocean. Southern California is the nation's largest importer of water; its imported water is used for both urban water supply and agriculture, especially irrigation. Water is supplied to Southern California not only from the Colorado River but also from Northern California and the Owens River Valley on the east side of the Sierra Nevada Mountains (NRC 1999).

Another form of water transfer that may have multiple impacts is groundwater extraction. First, as the water table drops, pumping of groundwater becomes increasingly difficult and expensive. Second, declining groundwater can often cause depleted stream flow and depleted local surface water supply. Finally, excessive groundwater extraction

can cause the ground to subside; subsidence of more than 9 m (29.5 ft) has been recorded in Southern California, and some formerly inhabited areas along the Gulf Coast are now inundated. Because of heavy irrigation, some areas also have excessive groundwater recharge. As water tables rise, the slightly saline groundwater can move to the surface by capillary action and evaporate, concentrating salt and other minerals at the surface, often damaging the soil, and polluting local groundwater (NRC 1999).

Water Security Issues

Once water supplies and systems are established, they may be vulnerable to drought, earthquakes, and terrorism. Drought affects more people than any other natural hazard, earthquakes can affect water security in modern urban communities, and terrorism is always a problem. Some are concerned that water scarcity might become the basis for future wars (Bruins 2000).

Droughts have led to crises and disasters throughout history and in many parts of the world. Drought may affect both developing and developed countries, and according to the United Nations' Office of Foreign Disaster Assistance, no other natural disaster has resulted in as many displaced persons in the twentieth century. For example, a drought in the Great Plains in the United States in the 1930s caused severe economic hardship in Missouri, Kansas, Nebraska, Oklahoma, South Dakota, and Arkansas. The Great Plains also experienced droughts in the 1950s, 1970s, and 1990s. One drought in Ethiopia affected more than 40 million people (Bruins 2000).

Unlike droughts, which are described as a creeping phenomenon, the damage associated with earthquakes is concentrated in time and space. In 1906, an earthquake in San Francisco caused numerous pipes to rupture and caused drowning of dozens of residents when broken water pipes flooded the Valencia hotel. It was impossible to control the firestorms that spread through the area, engulfing many buildings with temperatures reported to have reached 2000°F (1093.2°C). In 1995, a major earthquake directly hit the city of Kobe, Japan (Great Hanshin Earthquake). The quake lasted 20 seconds; 6,434 people died, 14,679 were injured, and 300,000 people were displaced. Of 67,421 fully collapsed structures, 6,985 were burned to the ground, and a citywide power failure and a near-citywide water supply failure occurred (Clark and Deininger 2001).

Even greater damage resulted from the 2011 Tōhoku earthquake, also known as the Great East Japan Earthquake. The resulting tsunami caused even greater damage than the Great Hanshin Earthquake. It is estimated that 45,700 buildings were destroyed and 144,300 were damaged. National police have reported 15,538 deaths, 5,685 injuries, and 7,060 people missing. At least 1.5 million households were reported to have lost access to water supplies (Wikipedia 2011).

Terrorism is also a very real, ongoing issue in our time. The President's Commission on Critical Infrastructure Protection concluded that the nation's water supply systems might be vulnerable to attack (Clark and Deininger 2000). According to Bruins (2000), Israel included Arab villages in the National Carrier System in order to limit the potential posed by terrorists. Water played an important role in the peace treaty that Israel and Jordan signed on Oct. 26, 1994. To this point, the worst-case scenarios have not materialized over water disputes in the Middle East.

Effects of Climate Change

Climate change may adversely affect water quality in streams and other raw water sources in the United States and consequently impact the design and operation of existing and future drinking water treatment plants. Increases in precipitation or precipitation intensity and resulting increases in runoff and stream flows can result in problematic turbidity levels, increased levels of organic matter, potentially high levels of pathogens, and increased levels of pesticides in lakes, rivers, and streams. Climate change may affect both surface water and groundwater quality. Although some areas may experience increases in runoff caused by shifts in the spatial and temporal distribution of precipitation, some areas may experience droughts resulting in elevated levels of potentially toxic algae and high concentrations of organic matter, bacteria, and so on (Whitehead et al. 2009, Interlandi and Crockett 2003, Jacobs et al. 2001). Some of these changes may have an adverse impact on the ability of water treatment plants (WTPs) to meet Safe Drinking Water Act (SDWA) regulations, thereby requiring treatment systems to make changes, sometimes major changes, in their operations.

Organization of Water Supplies in the United States

Water supplies in the United States were initially constructed in cities primarily for fire prevention, but most were eventually adapted to serve commercial and residential properties with water. The first US municipal water utility was established in Boston in 1652 to provide domestic water and fire protection (Hanke 1972). By 1860, 136 water systems operated in the United States, most of which supplied water from springs low in turbidity and relatively free from pollution (Baker 1949). Today, more than 162,000 water systems in the United States meet the federal definition of a public water system (USEPA 2005b).

Water utilities in the United States vary greatly in size, ownership, and type of operation. The SDWA defines public water systems as consisting of community water supply systems; transient noncommunity water supply systems; and nontransient noncommunity water supply systems. A community water supply system serves year-round residents and ranges in size from those that serve as few as 25 people to those that serve several million. A transient noncommunity water supply system serves areas such as campgrounds or gas stations where people do not remain for long periods of time. A nontransient noncommunity water supply system serves primarily nonresidential customers but must serve at least 25 of the same people for at least six months of the year (such as schools, hospitals, or factories that have their own water supply). Thirty-three percent (52,838) of these systems are categorized as community water supply systems, 55 percent are categorized as transient noncommunity water supplies, and 12 percent (19,375) are nontransient noncommunity water systems (USEPA 2005b).

Overall, public water systems serve 297 million residential and commercial customers. Most systems (98 percent) serve less than 10,000 people, but almost three quarters of all Americans get their water from community water supplies serving more than 10,000 people (USEPA 2005b). Not all water supplies deliver water directly to consumers, but rather deliver water to other supplies. Community water supply systems are defined as “consecutive systems” if they receive their water from another community water supply through one or more interconnections (Fujiwara et al. 1995).

Some utilities rely primarily on surface water supplies while others rely primarily on groundwater. Surface water is the primary source of 22 percent of the community water supply systems, while groundwater is used by 78 percent of community water supply systems. Of the noncommunity water supply systems (both transient and nontransient), 97 percent are served by groundwater. Many systems serve communities using multiple sources of supply such as a combination of groundwater and/or surface water sources. In a grid/looped system, the mixing of water from different sources can have a detrimental influence on water quality, including taste and odor, in the distribution system (Clark et al. 1988; 1991a,b).

Some utilities, like the one operating in New York City, own large areas of the watersheds from which their water source is derived, while other utilities depend on water pumped directly from major rivers like the Mississippi River or the Ohio River, and therefore own little if any watershed land. The SDWA was amended in 1986 and again in 1996 to emphasize source water protection in order to prevent microbial contaminants from entering drinking water supplies (Borst et al. 2001). Owning or controlling its watershed provides an opportunity for a drinking water utility to exercise increased control of its source water quality (Peckenham et al. 2005).

The water supply industry in the United States has a long history of local government control over operation and financial management, with varying degrees of oversight and regulation by state and federal government. Water supply systems serving cities and towns are generally administered by departments of municipalities or counties (public systems) or by investor-owned companies (private systems). Public systems are predominantly owned by local municipal governments, and they serve approximately 78 percent of the total population that uses community water supplies. Approximately 82 percent of urban water systems (those serving more than 50,000 persons) are publicly owned. About 33,000 privately owned water systems serve the remaining 22 percent of people served by community water systems. Private systems are usually investor-owned in the larger population size categories but can include many small systems as part of one large organization. These investor-owned utilities are in business to generate profits for their shareholders. In the small- and medium-sized categories, the privately owned systems tend to be owned by homeowners, associations, or developers, and they simply provide water to their clientele with little regard for profit. Finally, several classifications of state-chartered public corporations, quasi-governmental units, and municipally owned systems exist that operate differently than traditional public and private systems. These systems include special districts, independent nonpolitical boards, and state-chartered corporations (NRC 2006). Table 1-1 provides a snapshot of the size and the population served for public water systems in the United States.

Common Elements in Water Systems

Distribution system infrastructure is a major asset of a water utility, even though most of the components are either buried or located inconspicuously. Drinking water distribution systems are designed to deliver water from a source (usually a treatment facility) in the required quantity and quality and at satisfactory pressure to individual consumers in a utility's service area. In general, to continuously and reliably move water between a source and a customer, the system would require storage reservoirs/tanks and a network of pipes, pumps, valves, and other appurtenances. This infrastructure is collectively referred to as the drinking water distribution system (Walski et al. 2003).

Table I-1. Size and the population served for public water systems in the United States in 2003 (USEPA 2005a)

System Size by Population Served		Very Small 500 or less	Small 501–3,300	Medium 3,301– 10,000	Large 10,001– 100,000	Very Large >100,000	Total
CWS	No. systems	30,417	14,394	4,686	3,505	361	53,363
	Pop. served	5,010,834	20,261,508	27,201,137	98,706,485	122,149,436	273,329,400
	% of systems	57%	27%	9%	7%	1%	100%
	% of pop.	2%	7%	10%	36%	45%	100%
NTNCWS	No. systems	16,785	2,786	97	16	2	19,686
	Pop. served	2,327,575	2,772,334	506,124	412,463	279,846	6,298,342
	% of systems	85%	14%	0%	0%	0%	100%
	% of pop.	37%	44%	8%	7%	4%	100%
TNCWS	No. systems	85,366	2,657	96	29	4	88,152
	Pop. served	7,315,647	2,602,706	528,624	619,248	12,269,000	23,335,225
	% of systems	97%	3%	0%	0%	0%	100%
	% of pop.	31%	11%	2%	3%	53%	100%
Total No. of systems		132,566	19,837	4,879	3,550	367	161,201

CWS = community water supply

NTNCWS = nontransient noncommunity water supply

TNCWS = transient noncommunity water supply

Impact of System Design and Operation on Water Quality

Based on the design and configuration of a particular system, many opportunities arise for water quality to change as water moves between the treatment plant and the consumer. These unwanted changes may occur for various reasons including: failures at the treatment barrier, transformations in the bulk phase, corrosion and leaching of pipe material, biofilm formation, and mixing between different sources of water. Many researchers have investigated the factors that influence water quality deterioration once it enters the distribution system. It has been well documented that bacteriological growth can cause taste-and-odor problems, discoloration, slime buildup, and economic problems, including corrosion of pipes and biodeterioration of materials. Bacterial numbers tend to increase during distribution and are influenced by several factors, including bacterial quality of the finished water entering the system, temperature, residence time, presence or absence of a disinfectant residual, construction materials, and availability of nutrients for growth (Geldreich et al. 1972, LeChevallier et al. 1987, Maul et al. 1985a and b, Zhang and DiGiano 2002, Camper et al. 2003).

The branch and grid/loop are the two basic configurations for most water distribution systems. A branch system is similar to that of a tree branch with smaller pipes branching off larger pipes throughout the service area. This type of system is most frequently used in rural areas, and the water has only one possible pathway from the source to the consumer. A grid/loop system is the most widely used configuration in large

municipal systems and consists of interconnected pipe loops throughout the area to be served. In this type of system, the water can follow several pathways from the source to the consumer. Transmission mains are typically 20 to 24 in. in diameter or larger. Dual-service mains that serve both transmission and distribution purposes are normally 12 to 20 in. in diameter. Distribution mains are usually 6 to 12 in. in diameter in every street. Service lines are typically 1 in. in diameter. Specific pipe sizes can vary depending on the extent of the distribution system and the magnitude of demand. Looped systems provide a high degree of reliability should a line break occur, because the break can be isolated with little impact on consumers outside the immediate area (Clark and Tippen 1990, Clark et al. 2004).

Storage Tanks/Reservoirs

Tanks and reservoirs are used to provide storage capacity to meet fluctuations in demand, to provide reserves for firefighting use and other emergency situations, and to equalize pressures in the distribution system (Boulos et al. 2006). The most frequently used type of storage facility is the elevated tank, but other types of tanks and reservoirs include in-ground tanks and open or closed reservoirs. Construction materials include concrete and steel. An issue that has drawn a great deal of interest is the problem of water turnover within storage facilities. Much of the water volume in storage tanks is dedicated to fire protection. Unless utilities make a deliberate effort to exercise (fill and draw) their tanks or to downsize the tanks when the opportunity presents itself, both water aging and water mixing problems can occur. The latter can lead to stratification and/or large stagnant zones within the water volume. Some of these issues will be discussed later in this book.

Pipe Network

The systems of pipes or *mains* that carry water from the source (such as a treatment plant) to the consumer are often categorized as transmission/trunk, distribution, and service mains. Transmission/trunk mains are usually designed to convey large amounts of water over long distances, such as from a treatment facility to a storage tank within the distribution system. Distribution mains are typically smaller in diameter than the transmission mains and generally follow city streets. Service mains are pipes that carry water from the distribution main to the building or property being served. Service lines can be of any size, depending on how much water is required to serve a particular customer, and are sized so that the utility's design pressure is maintained at the customer's property for the desired flows.

The most commonly used pipes today for water mains are ductile iron, prestressed concrete, polyvinyl chloride (PVC), reinforced plastic, and steel. In the past, unlined cast-iron pipe and asbestos-cement pipes were frequently used. Even a medium-sized water utility may have hundreds of miles of pipes constructed from various types of materials, ranging from new, lined, or plastic pipes to unlined pipes that are more than 50 years old. Over time, biofilms and tubercles attached to pipe walls can result in both loss of carrying capacity and a significant loss of disinfectant residual, thereby adversely affecting water quality (Clark and Tippen 1990).

The mains should be placed in areas along the public right of way, which provides for ease of access, installation, repair, and maintenance. Broken or leaking water mains should be repaired as soon as possible to minimize property damage and loss of water. In the past, it has been standard practice to maintain the carrying capacity of the pipe in

the distribution system as high as possible to provide the design flow and keep pumping costs as low as possible. However, there has been recent concern that excess capacity can lead to long residence times and thus contribute to deterioration in water quality.

Valves

Two general types of valves are found in a distribution system: isolation valves and control valves. Isolation valves are used in the distribution system to isolate sections for maintenance and repair and are typically located in a system so that the areas isolated will cause a minimum of inconvenience to other service areas. Maintenance of the valves is one of the major activities carried out by a utility. Many utilities have a regular valve-turning program in which a percentage of the valves are opened and closed on a regular basis. It is desirable to turn each valve in the system at least once per year. In large systems, this may or may not be practical, but periodic exercise and checking of valve operations should occur. This practice minimizes the likelihood that valves will become inoperable due to corrosion. The implementation of such a program ensures that, especially during an emergency, water can be shut off or diverted and that valves have not been inadvertently closed.

Control valves are used to regulate the flow or pressure in a distribution system. Typical types of control valves include pressure-reducing valves, pressure-sustaining valves, flow control valves, throttling valves, and check valves.

Pumps

Pumps are used to impart energy to the water in order to boost it to higher elevations or to increase pressure. Routine maintenance, proper design and operation, and testing are required to ensure that they will meet their specific objectives. Pump tests are typically run every 5 to 10 years to check the head-discharge relationship for the pump. Many system designers recommend two smaller pumps instead of one large pump to ensure redundancy.

Hydrants and Other Appurtenances

Hydrants are primarily a part of the firefighting infrastructure of a water system. Although water utilities usually have no legal responsibility for fire flow, developmental requirements often include fire flows, and thus distribution systems are designed to support needed fire flows where practical (AWWA 2008). Proper design, spacing, and maintenance are needed to ensure an adequate flow to satisfy firefighting requirements. Fire hydrants are typically exercised and tested periodically by water utility or fire department personnel. Fire-flow tests are conducted periodically to satisfy the requirements of the Insurance Services Office (ISO 2003) or as part of a water distribution system calibration program. Other appurtenances in a water distribution system include blow-off valves and air-release valves.

Basic Design and Operational Philosophies

A detailed understanding of *how water is used* is critical to understanding water distribution system design and operation. Almost universally, the manner in which industrial and residential customers use water drives the overall design and operation of a water distribution system. Generally, water use varies both spatially and temporally. Besides

customer consumption, a major function of most distribution systems is to provide adequate standby fire-flow capacity (Fair and Geyer 1971). For this purpose, fire hydrants are installed in areas that are easily accessible by firefighters and are not obstacles to pedestrians and vehicles. The ready-to-serve requirements for firefighting are governed by the National Fire Protection Association (NFPA), which establishes standards for firefighting capacity of distribution systems (Cote et al. 2008). In order to satisfy this need for adequate standby capacity and pressure (as mentioned earlier), most distribution systems use standpipes, elevated tanks, and large storage reservoirs. Additionally, most distribution systems are *zoned*. Zones are areas or sections of a distribution system of relatively constant elevation. Zones can be used to maintain relatively constant pressures in the system over a range of ground elevations. Sometimes, zone development occurs as a result of the manner in which the system has expanded.

Conservative design philosophies, aging water supply infrastructure, and increasingly stringent drinking water standards have resulted in concerns over the viability of drinking water systems in the United States. Questions have been raised over the structural integrity of these systems as well as their ability to maintain water quality from the treatment plant to the consumer. The *Clean Water and Drinking Water Infrastructure Gap Analysis* (USEPA 2002), which identified potential funding gaps between projected needs and spending from 2000 through 2019, estimated a potential 20-year funding gap for drinking water capital and operations and maintenance, ranging from \$45 billion to \$263 billion, depending on spending levels. Based on current spending levels, the United States faces a shortfall of \$11 billion annually to replace aging facilities and comply with safe drinking water regulations. Federal funding for drinking water in 2005 remained level at \$850 million—less than 10 percent of the total national requirement (ASCE 2005). Parts of many systems are approaching or exceed 100 years old, and an estimated 26 percent of the distribution system pipe in this country is unlined cast iron and steel in poor condition. At current replacement rates for distribution system components, it is projected that a utility will replace a given pipe every 200 years (Kirmeyer et al. 1994). Grigg (2005) provides comprehensive guidance to utilities on how to assess options for distribution system renewal. Grigg's (2005) report contains a knowledge base on condition assessment, planning and prioritization, and renewal methods.

The effect of designing and operating a system to maintain adequate fire flow and redundant capacity can result in long travel times for water between the treatment plant and the consumer. These long travel times and low velocities may be detrimental to meeting the drinking water maximum contaminant levels (MCLs). Long residence times may lead to formation of disinfection by-products (DBPs), loss of disinfectant residuals, bacterial growth, and formation of biofilm.

Nonpotable waters (e.g., sea, river, and lake water) without adequate treatment have been used for fire protection for many years, often with disastrous results. However, reclaimed wastewater (in cases where its quality is better managed than the aforementioned unregulated sources) has been effectively used for providing fire protection. St. Petersburg, Fla., has been operating such a system to bolster fire-protection capacity since 1976. The reclaimed water hydrants are distinguished from potable water hydrants by color and their special valves. If the reclaimed water system is designed for fire protection, the potable water piping can have a very small diameter and investments can be made in higher quality pipe materials, which, with much shorter residence time in the system, would vastly improve the quality of the water at the tap. With this in mind, where retrofitting one of the two systems is necessary, it might be wiser to use the existing

potable water system for the reclaimed water and retrofit with new, high-quality, smaller potable water lines (Okun 1996).

Many systems serve communities with multiple sources of supply, such as a combination of wells and/or surface sources. In a grid/looped system, this configuration will influence water quality in a distribution system because of the effect of mixing of water from these different sources. These interactions are a function of complex system hydraulics (Clark et al. 1988, Clark et al. 1991a). Water quality models can be very useful in defining mixing and blending zones within water utility distribution networks. Mixing of water in a network can result in taste and odor problems or other water quality problems and can influence maintenance, repair, and rehabilitation procedures.

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Chapter 2

Public Health and Regulatory Issues in Water Supply

Introduction

Water is absolutely essential for human existence. The human body consists of 65 to 70 percent water, and an active person loses approximately 2 L (0.53 gal) of water every day through exhaling, urine, stools, and perspiration. These lost fluids must be replaced, and in hot climates the amount of replacement liquid may be as high as 5 to 10 L (1.32–2.64 gal) of water per day. The number of days a healthy person can survive without water is limited and is temperature dependent. In a moderate temperature range of 16–21°C (61–70°F), the survival period is approximately 18 days, but in a more extreme environment of 39–49°C (102.2–120.2°F), the survival period is about 2 days. The stages of dehydration for an 80-kg (176-lb) person are as follows (Bruins 2000):

- A loss of 3.2 L (0.85 gal) of water (4 percent loss in body weight) leads to a feeling of apathy.
- A loss of 6.4 L (1.70 gal) of water (8 percent loss in body weight) leads to a condition in which it becomes very difficult to speak.
- A loss of 9.6 L (2.54 gal) of water (12 percent loss of body weight) leads to situation where it becomes impossible to swallow and a person can only be saved by the infusion of intravenous fluids.
- A loss of 14.4 L (3.80 gal) of water (18 percent loss in body weight) usually results in death.

Obviously the quantity of water consumed is important, but water quality is equally significant, and water should be free from chemical and biological contaminants. Each year, millions of people, particularly children, die from diarrhea caused by contaminated drinking water. Water-related diseases include waterborne infections such as cholera, typhoid, infective hepatitis, schistosomiasis, and guinea worm.

In the United States, drinking water treatment has played a major role in protecting public health by reducing waterborne disease. For example, the typhoid death rate for one year in the 1880s was 158 per 100,000 in Pittsburgh, Pa. (Fujiwara et al. 1995). Similarly, both typhoid case and death rates for the city of Cincinnati declined more than tenfold during the period 1898 to 1928 because of the use of sand filtration, disinfection via chlorination, and the application of drinking water standards (Clark et al. 1985). By 1935, the typhoid death rate had declined to 5 per 100,000. Such reductions in waterborne disease outbreaks were brought about by the use of sand filtration, disinfection, and the application of drinking water standards (Clark et al. 1991b). By the end of the nineteenth century,

however, waterborne disease had become recognized as a serious problem in industrialized river valleys. This led to the more routine use of water treatment prior to its distribution. Figure 2-1 shows the decline in typhoid incidence rate for the Cincinnati Water Works, and Figure 2-2 shows a similar decline for the death rate during this period.

It is generally accepted that water treatment in the United States has been a major contributor to safeguarding the nation's public health. Such dramatic reductions in waterborne disease outbreaks were brought about by the application of drinking water standards and "multiple barriers" of protection. The multiple-barrier concept includes the use of conventional treatment (e.g., sand filtration) in combination with disinfection to provide safe and aesthetically acceptable drinking water. Residual disinfectant levels serve to protect water quality within a distribution system prior to its delivery (Clark et al. 1991a).

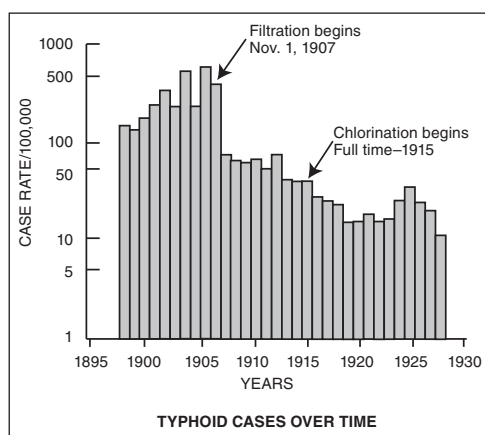


Figure 2-1. Typhoid case rate for Cincinnati Water Works (Clark et al. 1985)

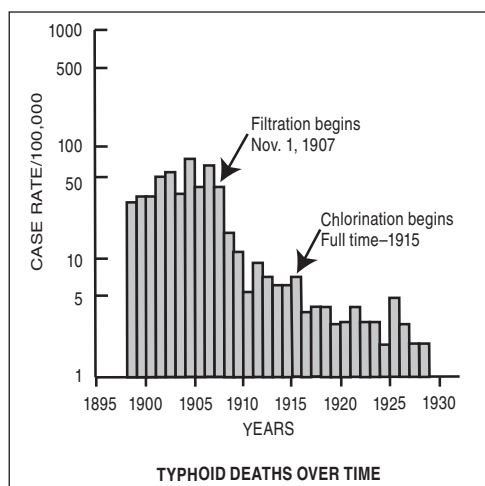


Figure 2-2. Typhoid death rate for Cincinnati Water Works (Clark et al. 1985)

However, periodically water supply problems have continued to surface. Some of the more notable water supply problems that occurred during the 1980s and 1990s in the United States are summarized in Clark and Grayman (1998). For example, in 1993 in Milwaukee, Wis., an estimated 400,000 water consumers were infected during a cryptosporidiosis outbreak. The number of deaths associated with this outbreak is estimated at nearly 100 immunocompromised individuals. Boil-water orders in the Manhattan borough of New York City and Washington, D.C., drew attention to drinking water problems in major metropolitan areas. In November 1993 in Gideon, Mo., out of a population of 1,000, 400–500 people contracted *Salmonella typhimurium* (Clark et al. 1996). The *Salmonella* outbreak contributed to the death of 7 of these individuals. It is believed that bird droppings contaminated storage tanks. During the period Dec. 15, 1989, to Jan. 20, 1990, residents and visitors to Cabool, Mo, population 2,090, experienced 240 cases of diarrhea and 6 deaths (Geldreich et al. 1992). The organism *Escherichia coli* serotype 0157:H7, associated with the feces of healthy dairy cattle, was isolated in many of the stool samples of ill people. As in the case of Gideon, Cabool used a nondisinfected groundwater. In both

situations, deaths were among the elderly in nursing homes. One consequence of these investigations is the finding that immunocompromised people (elderly and young) are often less capable of surviving waterborne illness than younger, healthier people (Clark et al. 1994a).

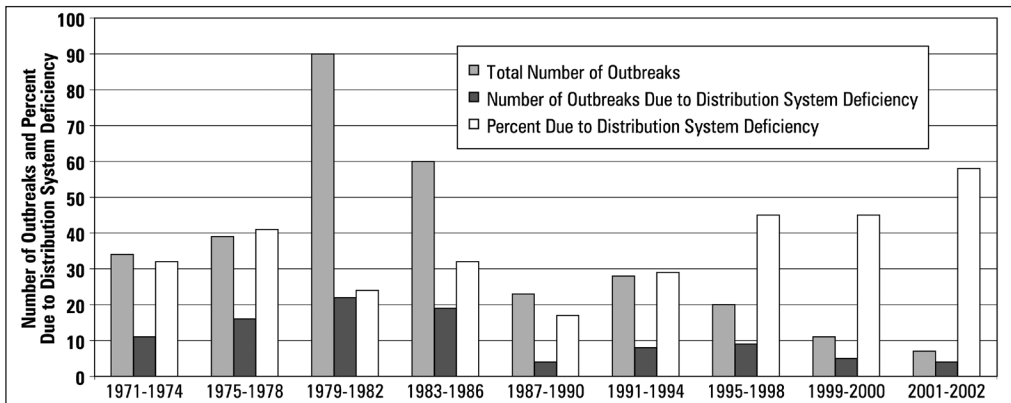


Figure 2-3. Waterborne disease outbreaks in community water systems (CWS) associated with distribution system deficiencies (Panguluri et al. 2005)

In addition, a rising number of giardiasis cases were reported especially in small communities in the 1980s and 1990s.

These types of problems are certainly not confined to the United States. A USEPA team was invited by the Centers for Disease Control and Prevention (CDC) to assist in evaluating the waterborne disease potential associated with a cholera outbreak in Peru in 1991. The investigative team concluded that one of the major factors in this outbreak was the marginal condition of the distribution systems in the areas visited. It was observed that water leaving a treatment plant had adequate disinfectant residuals that quickly disappeared within the distribution system. Systems experienced intermittent operation, fluctuating pressures, frequent pipe breaks, high water losses, and unplanned cross-connections. Little repair and maintenance were practiced by the utilities visited. It was the opinion of the investigative team that many of the waterborne disease problems associated with cholera were related to improperly operated and poorly maintained distribution systems (Clark et al. 1993a).

The National Research Council (NRC 2006) examined the causes of waterborne outbreaks in the United States reported by various investigators between 1971 and 2004. Figure 2-3 presents the total number and proportion of waterborne diseases associated with distribution system deficiencies.

The Distribution System as a Barrier to Waterborne Disease

Developing an effective drinking water infrastructure is essential to public health, spurs productivity and profitability, increases the tax base, and creates skilled jobs in construction, engineering, and manufacturing (Clark et al. 1988, Clark et al. 1993b). On the one hand, it has been estimated that 57,000 jobs are created for every \$1 billion invested in distribution infrastructure (Kirmeyer et al. 1994). On the other hand, improperly designed and maintained systems can be an economic liability.

An infrequently considered factor that may influence water quality in a distribution system is the effect of mixing water from different sources. Water distribution systems frequently draw water from multiple sources, such as a combination of wells and/or surface sources. The mixing of waters from different sources that takes place within a distribution system is a function of complex system hydraulics (Clark and Grayman 1998, Clark et al. 1991a, Clark et al. 1991c).

Much has been written about the multiple-barrier concept and its application in providing protection against waterborne disease (Clark et al. 1993a). The multiple-barrier concept has traditionally referred to the use of conventional treatment in combination with disinfection to provide safe and aesthetically acceptable drinking water. However, the distribution system may be the final barrier against waterborne disease.

Water Quality Deterioration in Distribution Systems

Even medium-sized water utilities may have hundreds of miles of pipes constructed from various types of materials, ranging from new lined pipes to unlined pipes that are more than 50 years old. Over time, biofilms and tubercles attached to pipe walls can result in a significant loss of disinfectant residual and, thereby, adversely affect water quality.

Many opportunities arise for water quality to change as it moves between the treatment plant and the consumer. Figure 2-4 illustrates some of the transformations that take place in the water flow through the pipe (bulk water phase) and at the pipe wall (Clark et al. 1994b). Cross-connections, failures at the treatment barrier, and transformations in the bulk phase can all degrade water quality. Corrosion, leaching of pipe material, and biofilm formation and scour

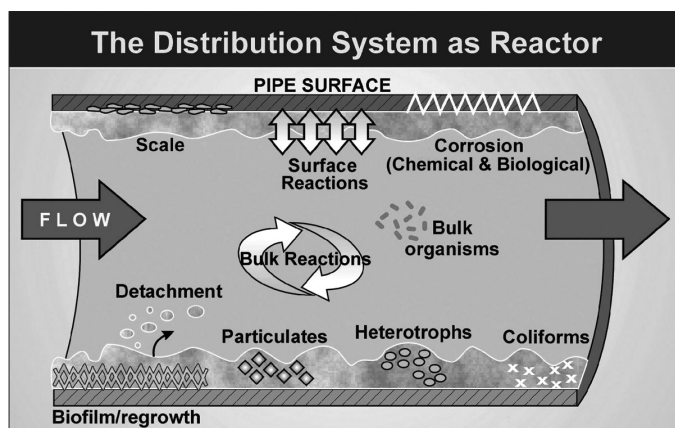


Figure 2-4. Transformations in the bulk phase and at pipe wall (Adapted from MSU-CBE, P. Dirckx)

can occur at the pipe wall to degrade water quality. Unlike hydraulic modeling of distribution systems, water quality modeling is a relatively recent development dating back only to the early 1980s. As will be discussed, water quality models can be used to trace the movement of contaminants in the water distribution system. These models may also be used to calculate the age of the water within the distribution system or to determine the source(s)

of water throughout the system. Water quality models generally use the results of hydraulic models and, like hydraulic models, may be based on either steady-state or extended-period simulation (EPS). Contaminants may be treated as either conservative (do not degrade) or as experiencing decay or growth as they move through the system. Many researchers have investigated how water deteriorates once it enters the distribution system. It has been documented that bacteriological quality changes can cause taste-and-odor problems, discoloration, slime growths, and economic problems, including corrosion of pipes and biodeterioration of materials. Bacterial numbers tend to increase during distribution and are influenced by a number of factors, including bacterial quality of the finished water entering the system, temperature, residence time, presence or absence of a disinfectant residual, construction materials, and availability of nutrients for growth (Geldreich et al. 1972, LeChevallier et al. 1987, Maul et al. 1985a and 1985b).

The relationship of bacteriological quality to turbidity and particle counts in distribution water was studied by McCoy and Olson (1986). One upstream and one downstream

sampling site in each of three distribution systems (two surface water supplies and one groundwater supply) were sampled twice per month over a one-year period. Degradation of bacterial water quality was shown to be the result of unpredictable intermittent events that occurred within the system.

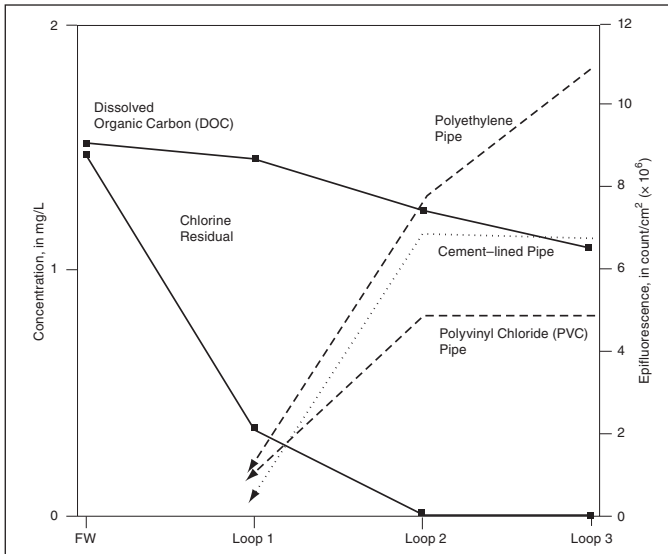


Figure 2-5. Loss of chlorine residuals and DOC and growth in bacterial populations for three different pipe materials with time in a distribution simulator

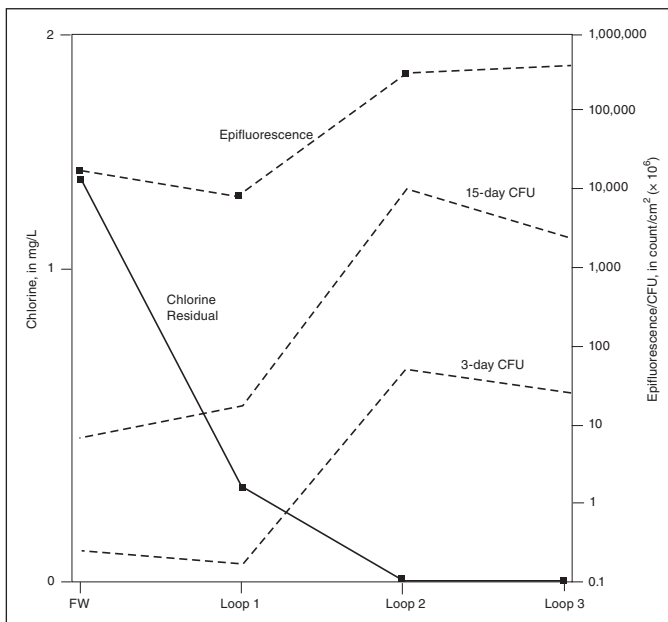


Figure 2-6. Loss of chlorine residuals and growth in bacterial populations with time in a distribution simulator

Figures 2-5, 2-6, and 2-7 illustrate some of the complex chemical and microbiological changes that take place in distribution networks (Clark et al. 1994b). These data are from a unique pilot facility in Nancy, France. The pilot facility consisted of two pilot plants operating in parallel, each feeding a separate simulated distribution system. The source of water for the pilot plant was a nondisinfected raw surface water. Each simulated system consisted of three pipe loops in series. Each of the loops had a one-day residence time.

It is difficult at this time, given our current level of knowledge, to predict changes in water quality during transport in a distribution network. However, as can be seen from these data, as the water moves through the loops, there is a tendency for the disinfectant residual to drop and for various measures of biological activity in the bulk phase to increase.

Based on the study in Nancy, Figure 2-5 illustrates the decrease in dissolved organic carbon (DOC) that took place as water traveled through the pilot network. This supports the assumption that

DOC was used for biological growth. The biofilm buildup increased with residence time in the loop and increased dramatically after disinfectant residuals disappeared. This is consistent with results obtained by LeChevallier et al. (1987). Polyethylene coupons sustained the highest biofilm buildup, perhaps caused by materials in the pipe that encourage biofilm growth. Clearly, differences in biofilm formation occur based on the type of pipe material.

Figure 2-5 shows the steady loss of disinfectant residual through the pipe loops. The chlorine residual dropped most rapidly because of its reaction with organic material in the bulk phase of the water and with the pipe wall material. As the residuals decreased, the organisms in the bulk water increased dramatically.

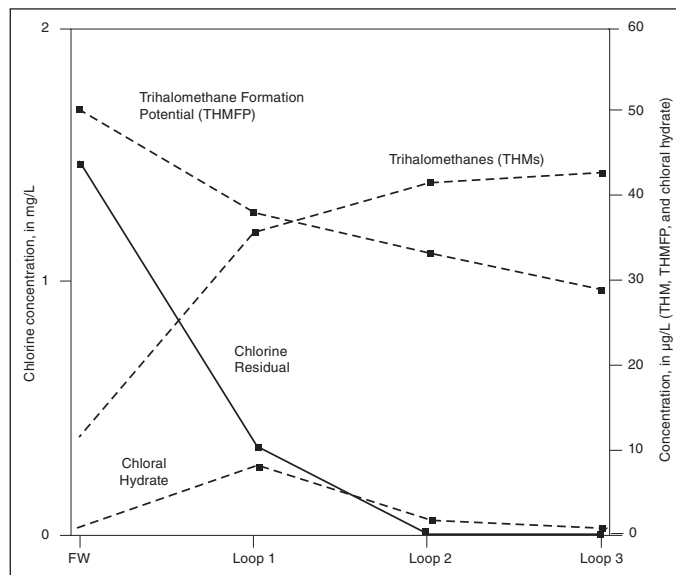


Figure 2-7. Loss of chlorine residuals and formation of disinfection by-products with time in ductile-iron pipe in a distribution simulator

residual dropped rapidly and was virtually gone by the end of the second loop. Instantaneous THMs exceeded THMFP at the end of loop 2, and instantaneous THMs continued to increase through the third loop. This might be explained by the increase and then decrease in chloral hydrate concentrations between the treatment plant and the end of the third loop. Chloral hydrate may be converted to THMs in the absence of chlorine. These results are consistent with other research that has shown this same phenomenon (Stevens et al. 1989).

As shown in Figure 2-6, bacterial populations increase over time in the distribution simulator as chlorine residual decreases. Based on the data presented, the bacterial populations seem to drop as they consume the available nutrients.

Figure 2-7 shows trihalomethane (THM) changes that took place across the pipe loops for postdisinfection with chlorine. The drop in trihalomethane formation potential (THMFP) was no doubt related to the consumption of DOC.

As shown in Figure 2-7, the disinfectant

Safe Drinking Water Act

Concerns about waterborne disease and uncontrolled water pollution resulted in a dramatic increase in federal water quality legislation between 1890 and 1970. Even though significant advances were made to eliminate waterborne disease outbreaks during that period, the focus of drinking water concerns began to change. By the 1970s, more than 12,000 chemical compounds were known to be in commercial use, and many more were being added each year. Many of these chemicals cause contamination of groundwater and surface water and are known to be carcinogenic and/or toxic. The passage of the Safe Drinking Water Act (SDWA) of 1974 was a reflection of concerns about chemical contamination (SDWA 1974).

On Dec. 16, 1974, the US Congress passed the SDWA, which authorized the US Environmental Protection Agency (USEPA) to promulgate the first set of federal regulations which would “protect health to the extent feasible, using technology, treatment techniques, and other means, which the Administrator determines are generally available (taking costs into consideration)” (SDWA 1974). As a result, a set of regulations was promulgated in 1975, which became effective June 24, 1977. These were known as the National Interim Primary Drinking Water Regulations (NIPDWR). The NIPDWR established enforceable maximum contaminant levels (MCLs) for 10 inorganic contaminants, 6 organic contaminants, turbidity, coliform, radium-226, radium-228, gross alpha activity, and man-made radionuclides. The NIPDWR also established monitoring and analytical requirements for determining compliance.

Amendments to the SDWA promulgated in 1986 required the US Environmental Protection Agency to establish maximum contaminant level goals (MCLGs) for each contaminant that may have an adverse health effect. Each goal is required to be set at a level at which no known or anticipated adverse effects on health occur, thereby allowing an adequate margin of safety (Clark et al. 1987). Maximum contaminant levels or enforceable drinking water standards must be set as close to MCLGs as feasible.

The 1996 amendments to the SDWA nearly doubled the text of the act and provided for several new programs and initiatives, including the following: encouraging capacity development on the part of drinking water utilities, guidelines for water conservation, a requirement for utilities to increase efforts at informing their customers as to their status in complying with drinking water regulations, establishing an infrastructure grants program, emphasizing the need to bring small systems into compliance, and creating a whole new emphasis on source water protection.

Originally, the emphasis on understanding, interpreting, and implementing the SDWA and its regulations was primarily focused on treated water. However, substantial evidence indicates that many factors can cause water quality to deteriorate between the treatment plant and the point of consumption. Some of these factors include the following: chemical and biological quality of source water; effectiveness and efficiency of treatment processes; adequacy of the treatment facility, storage facilities, and distribution system; age, type, design, and maintenance of the distribution network; and quality of treated water (Clark and Coyle 1990).

Most of the regulations established under the SDWA were promulgated with little understanding of the effect that the distribution system can have on water quality. However, the SDWA has been interpreted as meaning that some MCLs shall be met at the consumers’ tap, and thus involves the entire distribution system.

Safe Drinking Water Act regulations that emphasize system monitoring include the Surface Water Treatment Rule (SWTR), the Total Coliform Rule (TCR), the Lead and Copper Rule (LCR), and the Stage 1 Disinfectants and Disinfection By-Products Rule (D/DBPR1) and the Stage 2 Disinfectants and Disinfection By-Products Rule (D/DBPR2) (originally the total trihalomethane regulation), which addresses trihalomethanes and haloacetic acids. The D/DBPR, SWTR, and TCR specify treatment and monitoring requirements that must be met by all public water suppliers.

The SWTR requires that a detectable disinfectant residual be maintained at representative locations in the distribution system to provide protection from microbial contamination. The TCR regulates coliform bacteria that are used as “surrogate organisms” to indicate whether or not system contamination is occurring. Monitoring for compliance with the Lead and Copper Rule is based entirely on samples taken at the consumer’s tap. The current standard for trihalomethanes (THMs) is 0.08 mg/L for systems serving more than 10,000 people,

but the D/DBPR imposes the current (or a reduced) THM level on all systems. This regulation also requires monitoring and compliance at selected monitoring points in the distribution system. Some of these regulations may, however, provide contradictory guidance. For example, the SWTR and TCR recommend the use of chlorine to minimize risk from microbiological contamination. However, chlorine or other disinfectants interact with natural organic matter (NOM) in treated water to form disinfection by-products (DBPs). Raising the pH of treated water will assist in controlling corrosion but will increase the formation of THMs.

A summary of the evolution of federal drinking water regulation since the passage of the SDWA in 1974 is presented in Figure 2-8.

In addition to the rules and regulations promulgated under the SDWA, security has recently become an issue for the water utility industry. Security of water systems is not a new issue. The potential for natural, accidental, and purposeful contamination of water supplies has been the subject of many studies. For example, in May 1998, President Bill Clinton issued Presidential Decision Directive (PDD) 63 that outlined a policy on critical infrastructure protection, including US water supplies. However, it was not until after Sept. 11, 2001, that the water industry focused on the vulnerability of the nation's water supplies to security threats. In recognition of these issues, President George W. Bush signed the Public Health Security and Bioterrorism Preparedness and Response Act of 2002 (Bioterrorism Act) into law in June 2002 (PL107-188). Under the requirements of the Bioterrorism Act, community water systems (CWSs) serving more than 3,300 people are required to prepare vulnerability assessments and emergency response plans. CWSs are public water systems (PWSs) that supply water to the same population throughout the year.

Table 2-1 summarizes the key requirements of the regulations presented in Figure 2-8 from a distribution system compliance perspective. However, no evidence suggests that current regulations have resulted in a reduction in the proportion of outbreaks attributable to distribution system-related factors. In 2000, the Federal Advisory Committee for the Microbial/Disinfection By-Products Rule recommended that USEPA evaluate available data and research on aspects of distribution systems that may create risks to public health. In 2003, USEPA committed to revising the TCR and is currently exploring the possibility of revising the TCR to provide a comprehensive approach for addressing water quality in the distribution system environment. To aid in this process, USEPA requested that the National Academies' Water Science and Technology Board conduct a study of water quality issues associated with public water supply distribution systems and their potential risks to consumers (NRC 2006). The revised TCR has been proposed and is now in review and will be discussed later. Recommendations from this study will be discussed later in this volume.

Some important distribution system water quality concerns are: maintenance of proper disinfectant levels; minimization of DBP formation; turbidity, taste, color, and odor issues; distribution tank mixing and utilization; main repair and pressure stabilization; flow management; cross-connection control; and backflow prevention. It should be noted that water quality goals can be difficult to achieve and can be contradictory. For example, an important goal is to maintain a positive disinfectant residual in order to protect against microbial contamination. However, DBPs (TTHMs) will increase as water moves through the network as long as disinfectant residual and NOM are available. Other DBPs (haloacetic acids [HAA5]) are degraded biologically when free chlorine or chloramines are nearly absent.

Table 2-1. Selected rules and regulations dealing with distribution systems (not inclusive) (Panguluri et al. 2005)

Regulation	Key Distribution System Requirements
Safe Drinking Water Act (SDWA)	Gives USEPA the authority to establish national primary and secondary drinking water regulations (MCLs and MCLGs).
National Interim Primary Drinking Water Regulations (NIPDWR)	The NIPDWR adopted at the passage of the SDWA required that representative coliform samples be collected throughout the distribution system.
Total Trihalomethane (TTHM) Rule	Established a standard for TTHMs as 0.08 mg/L.
1986 Amendments to the Safe Drinking Water Act (86SDWAA)	Established the MCLG concept.
Total Coliform Rule (TCR)	Regulates coliform bacteria, which are used as surrogate organisms to indicate whether or not treatment is effective and system contamination is occurring.
Surface Water Treatment Rule (SWTR)	Requires using chlorine or some other disinfectant.
Lead and Copper Rule (LCR)	Monitoring for compliance with the LCR is based entirely on samples taken at the consumer's tap.
Information Collection Rule (ICR)	Provided data to support the interim and long-term enhanced SWTR, and D/DBPR2.
1996 Amendments to the Safe Drinking Water Act (96SDWAA)	Has many provisions dealing with distribution systems, including the role that surface water quality can play in influencing the quality of distributed water.
Interim Enhanced Surface Water Treatment Rule (IESWTR)	Provisions to enhance protection from pathogens, including <i>Cryptosporidium</i> , and intended to prevent increases in microbial risk while large systems comply with the D/DBPR1.
Stage 1 Disinfectants and Disinfection By-Products (D/DBPR1)	This standard applies to all haloacetic acids (HAAs) and lowered the standard for TTHMs from 0.1 mg/L to 0.08 mg/L for community water supplies in the United States and requires monitoring and compliance at selected points in the distribution system.
Long Term Interim Enhanced Surface Water Rule 1 (LT1ESWTR)	Provisions to enhance protection from pathogens, including <i>Cryptosporidium</i> , and prevent increases in microbial risk for systems serving less than 10,000 people while they comply with the D/DBPR1.
Stage 2 Disinfectants and Disinfection By-Products Rule (D/DBPR2)	Requiring systems delivering disinfected water to meet maximum contaminant levels as an average at each compliance monitoring location (instead of as a systemwide average as in previous rules) for total trihalomethanes (TTHMs) and five haloacetic acids (HAA5). The rule targets systems with the greatest risk and builds incrementally on existing rules. Intended to reduce DBP exposure and related potential health risks and provide more equitable public health protection.

(continued)

Table 2-1. Selected rules and regulations dealing with distribution systems (not inclusive) (Panguluri et al. 2005) (continued)

Long Term Enhanced Surface Water Treatment Rule 2 (LT2ESWTR)	The LT2 Enhanced Surface Water Treatment Rule is intended to reduce incidence of disease associated with <i>Cryptosporidium</i> and other pathogenic microorganisms in drinking water. The rule applies to all public water systems that use surface water or groundwater that is under the direct influence of surface water. The rule will bolster existing regulations and provide a higher level of protection for drinking water supplies by: • Targeting additional <i>Cryptosporidium</i> treatment requirements to higher-risk systems • Requiring provisions to reduce risks from uncovered finished water storage facilities • Providing provisions to ensure that systems maintain microbial protection as they take steps to reduce the formation of disinfection by-products.
Revised Total Coliform Rule (RTCR)	The proposed RTCR shifts the regulatory focus to assessment of potential problems in the distribution system and fixing those problems, as appropriate. It proposes: • Removing the maximum contaminant level goal (MCLG) and maximum contaminant level (MCL) of zero for total coliforms and the associated public notice for total coliforms • Setting triggers for assessment and corrections that parallel the previous MCL for total coliforms • Maintaining a zero MCLG and MCL for <i>E. coli</i> • Introducing a tiered approach for assessment and corrections

Recommendations From the NRC Report

As mentioned previously, the National Research Council of the National Academy of Sciences (NAS) convened a committee on Public Water Supply Distribution Systems: Assessing and Reducing Risks in 2004. It released a report of its findings on Sept. 8, 2006, entitled *Drinking Water Distribution Systems: Assessing and Reducing Risks* (NRC 2006). Risk was defined as the possibility of suffering harm from a hazard. The report suggests that the distribution system is the remaining component of public water supplies yet to be adequately addressed in national efforts to eradicate waterborne disease. The report recommends that the USEPA should focus on working with representatives from states, water systems, and local jurisdictions to establish the elements that constitute acceptable cross-connection control programs. Existing plumbing codes should be consolidated into one uniform national code that utilities develop. The report recommends that:

- Storage facilities should be inspected on a regular basis.
- Better sanitary practices are needed during installation, repair, replacement, and rehabilitation of distribution system infrastructure.
- Water residence times in pipes, storage facilities, and premise plumbing should be minimized.
- Positive water pressure should be maintained.

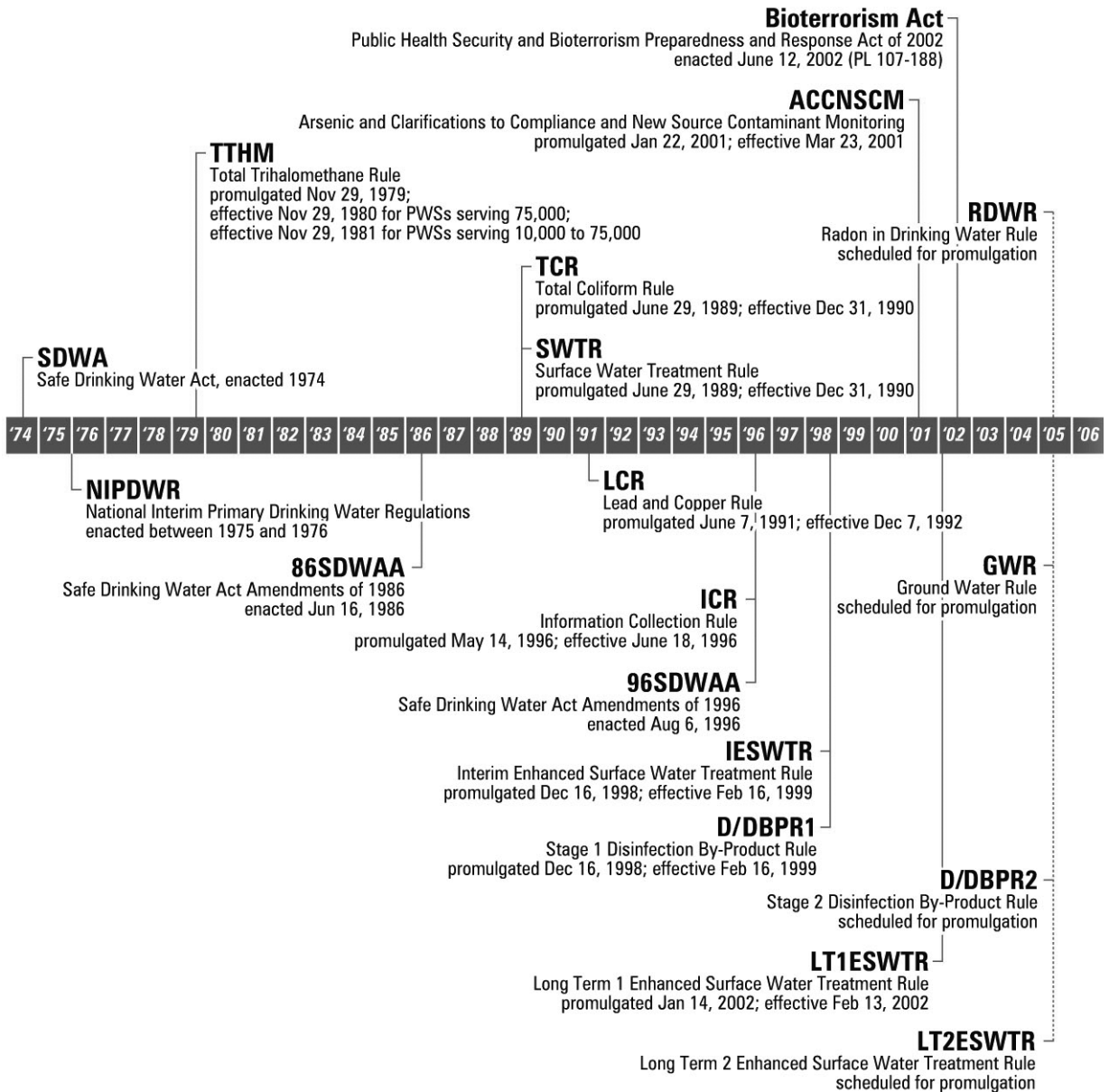


Figure 2-8. Evolution of safe drinking water regulations in the United States (Panguluri et al. 2005)