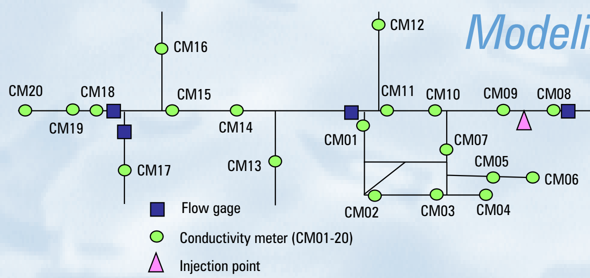
United States Environmental Protection Agency

Water Distribution System Analysis: Field Studies, Modeling and Management

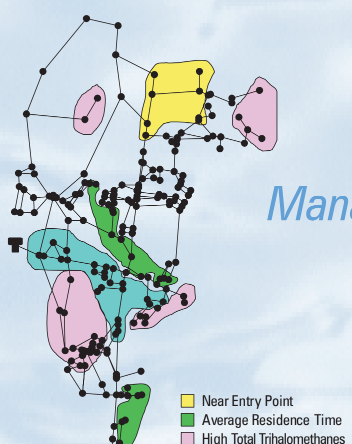
A Reference Guide for Utilities

Field Studies

Modeling



Management



EPA/600/R-06/028
December 2005

Water Distribution System Analysis: Field Studies, Modeling and Management

A Reference Guide for Utilities

U. S. Environmental Protection Agency

Office of Research and Development
National Risk Management Research Laboratory
Water Supply and Water Resources Division
Cincinnati, Ohio

Recycled/Recyclable
Printed with vegetable-based ink on paper that contains a minimum of 50% post-consumer fiber content processed chlorine free

Notice

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and groundwater; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

Table of Contents Overview

Table of Contents

List of Tables

List of Figures

Acronyms and Abbreviations

AC	Alternating Current
ACCNSCM	Arsenic and Clarifications to Compliance and New Source Contaminant Monitoring
ADAPT	Areal Design and Planning Tool
ADEQ	Arizona Department of Environmental Quality
$Al_2(SO_4)_3$	Aluminum Sulfate
AM/FM	Automated Mapping (or Asset Management)/Facilities Management
AMR	Automated Meter Reading
ASCE	American Society of Civil Engineers
ATSDR	Agency for Toxic Substances and Disease Registry
AWWA	American Water Works Association
AwwaRF	Awwa Research Foundation
C	Coefficient of Roughness
ClO_4	Perchlorate Anion
$CaCl_2$	Calcium Chloride
CAD	Computer-Aided Design
CADD	Computer-Aided Design and Drafting
CDC	Centers for Disease Control and Prevention
CFD	Computational Fluid Dynamics
CIS	Customer Information System
CM	Continuous Monitoring
COGO	Coordinated Geometry
CRT	Cathode Ray Tube
CWS	Contamination Warning System
DBP	Disinfection By-Products
DBPR1	Disinfectant By-Product Rule - Stage 1
DBPR2	Disinfectant By-Product Rule - Stage 2
DC	Direct Current
D.C.	District of Columbia
DEM	Digital Elevation Model
DIME	Dual Independent Map Encoding
DLG	Digital Line Graph
DSOP	Distribution System Water Quality Optimization Plan
DSS	Distribution System Simulator
DTM	Digital Terrain Model
DWQM	Dynamic Water Quality Model
EBMUD	East Bay Municipal Utility District
EDM	Electronic Distance Measurement
EMPACT	Environmental Monitoring for Public Access and Community Tracking
EOSAT	Earth Observation Satellite
EPA	U.S. Environmental Protection Agency
EPS	Extended Period Simulation
ESSA	Environmental Science Services Administration
EWS	Environmental Warning System
FC	Fecal Coliform
$FeCl_3$	Ferric Chloride
FOH	Federal Occupational Health
GA	Genetic Algorithm
gal	Gallon
GBF	Geographic Base File
GC	Gas Chromatograph
GCWW	Greater Cincinnati Water Works
GIS	Geographic Information System
GPD	Gallons Per Day
gpm	Gallons Per Minute
GPS	Global Positioning System
GRASS	Geographic Resources Analysis Support System
GUI	Graphical User Interface
GWR	Ground Water Rule
HAA	Haloacetic Acid
HAA5	The five Haloacetic Acids
HACCP	Hazard Analysis Critical Control Point
HGL	Hydraulic Grade Line
HSPP	Health and Safety Project Plan
ICR	Information Collection Rule
IDSE	Initial Distribution System Evaluation
IESWTR	Interim Enhanced Surface Water Treatment Rule
ILSI	International Life Sciences Institute
I/O	Input/Output
ISE	Ion Selective Electrode
ISO	Insurance Services Office
LCR	Lead and Copper Rule

LIFO	Last In/First Out
LIMS	Laboratory Information Management System
LIS	Land Information System
LT1ESWTR	Long Term 1 Enhanced Surface Water Treatment Rule
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
LVVWD	Las Vegas Valley Water District
ma	Milli-Amperes
MCL	Maximum Contaminant Level
MCLG	Maximum Contaminant Level Goal
MDL	Minimum Detection Limit
MDNR	Missouri Department of Natural Resources
MDOH	Missouri Department of Health
MGD	Million Gallons per Day
mg/L	milligrams per liter
MIT	Massachusetts Institute of Technology
MOC	Master Operating Criteria
MRDLG	Maximum Residual Disinfectant Level Goals
MS	Mass Spectrometer
MSU	Montana State University
NaCl	Sodium Chloride
NAD27	North American Datum of 1927
NAD83	North American Datum of 1983
NAPP	National Aerial Photography Program
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association
NHAP	National High Altitude Photography
NIPDWR	National Interim Primary Drinking Water Regulations
NJDHSS	New Jersey Department of Health and Senior Services
NMWD	North Marin Water District
NPL	National Priorities List
NPWA	North Penn Water Authority
NOM	Naturally Occurring Organic (and/or Inorganic) Matter
NRC	National Research Council
O&M	Operations and Maintenance
OCMS	Online Contaminant Monitoring System
ODBC	Open Database Connectivity
ORD	Office of Research and Development
ORP	Oxidation Reduction Potential
PAB3D	A Three-Dimensional Computational Fluid Dynamics Model developed by Analytical Services & Materials, Inc.
PC	Personal Computer
PDD	Presidential Decision Directive
PHRP	Public Health Response Plan
PL	Public Law
POE	Point of Entry
POGA	Progressive Optimality Genetic Algorithm
psi	Pounds Per Square Inch
PVC	Polyvinyl Chloride
PWS	Public Water System
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control
RDBMS	Relational Database Management Systems
RDWR	Radon in Drinking Water Rule
SAN	Styrene Acrylonitrile
SCADA	Supervisory Control and Data Acquisition
SCCRWA	South Central Connecticut Regional Water Authority
SDMS	Spatial Database Management System
SDWA	Safe Drinking Water Act
SDWAA	Safe Drinking Water Act Amendments
SMP	Standard Monitoring Program
SNL	Supply Node Link
SOP	Standard Operating Procedure
SPC	State Plane Coordinates
SSS	System Specific Study
SVOC	Semivolatile Organic Compound
SWTR	Surface Water Treatment Rule
SYMAP	Synagraphic Mapping
T&E	Test and Evaluation
TCE	Trichloroethylene
TCR	Total Coliform Rule
TEVA	Threat Ensemble Vulnerability Assessment
THM	Trihalomethane
TIGER	Topologically Integrated Geographic Encoding and Referencing

TIN	Triangulated Irregular Network
TIROS1	Television and Infrared Observation Satellite 1
TOC	Total Organic Carbon
TT	Treatment Technique
TTHM	Total Trihalomethane
TV	Television
U.S.	United States
UF	Ultrafiltration
UHF	Ultra High Frequency
UV	Ultraviolet
UV-Vis	Ultraviolet-Visible
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VHF	Very High Frequency
WASA	Water and Sewer Authority
WATERS	Water Awareness Technology Evaluation Research and Security
WQP	Water Quality Parameter
WRC	Water Research Centre
WSSM	Water Supply Simulation Model
WSTP	Wells, Storage Tanks, and Pumps
WTP	Water Treatment Plant

Acknowledgments

EPA would like to acknowledge the principal authors of the document, "Water Distribution System Analysis: Field Studies, Modeling, and Management," a Reference Guide for Utilities. The authors were Mr. Srinivas Panguluri, P.E. (Shaw Environmental, Inc.), Dr. Walter M. Grayman, P.E. (W.M. Grayman Consulting Engineer), and Dr. Robert M. Clark, P.E., D.E.E. (Environmental Engineering and Public Health Consultant). The work was performed under EPA Contract No. EP-C-04-034, Work Assignment No. 0-08 and 1-08, with Shaw Environmental, Inc.

EPA acknowledges the significant contributions from Mr. David J. Hartman and Dr. Yeongho Lee, P.E., of the Greater Cincinnati Water Works. Mr. Hartman and Dr. Lee served as external reviewers and directly contributed to the development of portions of this document. Greater Cincinnati Water Works also participated significantly in the field tracer tests that served as a foundation for the development of this document.

EPA acknowledges the peer reviews by the following utility personnel: Mr. William R. Kirkpatrick and Mr. Ronald B. Hunsinger of East Bay Municipal Utility District, and Mr. Arnold Strasser, P.E., of Denver Water.

EPA also acknowledges the peer reviews provided for this document by Dr. Fran A. DiGiano, P.E., of University of North Carolina, Mr. Morris L. Maslia, P.E., D.E.E., of the Agency for Toxic Substances and Disease Registry, Dr. Edward A. McBean, P.E., of University of Guelph, Dr. Vanessa L. Speight, P.E., of Malcolm Pirnie, Ms. L. Michelle Moore of National Drinking Water Clearinghouse, and Mr. E. Radha Krishnan, P.E., of Shaw Environmental, Inc.

EPA also gratefully acknowledges the following contributors to this document: Mr. Daniel R. Quintanar of Tucson Water, Ms. Laura B. Jacobson, P.E., Mr. Sridhar Kamojjala, P.E., and Mr. Mao Fang, P.E., of Las Vegas Valley Water District, Mr. Morris L. Maslia, P.E., D.E.E., of the Agency for Toxic Substances and Disease Registry, Dr. William B. Samuels, P.E., of SAIC, Dr. Mark W. LeChevallier and Dr. Kala K. Fleming of American Water.

EPA Contributors

Ms. Shirley J. Gibson functioned as Project Officer of EPA Contract No. EP-C-04-034, Ms. Lucille M. Garner served as Work Assignment Manager and Mr. Craig L. Patterson, P.E., served as the Alternate Work Assignment Manager and technical reviewer for this document. Mr. Roy C. Haught served as EPA Technical Advisor. Mr. Jonathan G. Herrmann, P.E., Mr. Kim R. Fox, P.E., D.E.E., and Dr. James A. Goodrich performed technical reviews of the document. Mr. Stephen M. Harmon was the EPA Quality Assurance Manager, and was responsible for the quality assurance review of the document. The document was also reviewed by many other EPA reviewers including the following: Mr. Blake L. Atkins, Mr. William H. Davis, Ms. Jean E. Dye, Mr. Robert J. Janke, Mr. Bruce A. Macler, Ms. Jill R. Neal, Dr. Lewis A. Rossman, P.E., Mr. Kenneth H. Rotert, Dr. Irwin J. Silverstein, P.E., D.E.E., and Ms. Elin A. Warn.

Chapter 1
Introduction

Drinking water utilities in the United States (U.S.) and throughout the world face the challenge of providing water of good quality to their consumers. Frequently, the water supply is derived from surface water or groundwater sources that may be subject to naturally occurring or accidentally introduced contamination (ILSI, 1999; Gullick et al., 2003). In other cases, routine upstream waste discharges or purposeful contamination of the water can diminish the quality of the water. The treated water may be transmitted through a network of corroded or deteriorating pipes. All of these factors can result in degradation in the quality of the water delivered to customers.

In the U.S., drinking water quality has to comply with federal, state, and local regulations. This is based on selected physical, chemical, and biological characteristics of the water. The U.S. Environmental Protection Agency (EPA) has promulgated many drinking water standards under the Safe Drinking Water Act (SDWA) of 1974. These rules and regulations require that public water systems (PWSs) meet specific guidelines and/or numeric standards for water quality. The SDWA defines a PWS as a system that serves piped water to at least 25 persons or 15 service connections for at least 60 days each year. For the purposes of this reference guide, PWSs are referred to as utilities.

The SDWA has established two types of numeric standards. The first type of standard is enforceable and referred to as a maximum contaminant level (MCL). The other non-enforceable standard is referred to as a maximum contaminant level goal (MCLG). MCLGs are set at a level at which no known or anticipated adverse human health effects occur. Where it is not economically or technologically feasible to determine the level of a contaminant, a treatment technique (TT) is prescribed by EPA in lieu of establishing an MCL. For example, *Giardia* is a microbial contaminant that is difficult to measure. To ensure proper removal, experimental work has established optimum treatment conditions for the water at a specified pH, temperature, and chlorine concentration for a specified length of time to achieve a fixed level of inactivation.

Compliance with MCL and TT requirements is typically ensured by requiring that water utilities periodically monitor various characteristics of the treated water. In summary, the EPA Guidelines and Standards are designed to ensure that drinking water is adequately treated and managed by water utilities to support public safety, protect public health, and promote economic growth (Clark and Feige, 1993).

Removing contaminants from drinking water can be expensive. Depending upon the type and level of contaminant(s) present in the source water, utilities can choose from a variety of treatment processes. These individual processes can be arranged in a "treatment train" (a series of processes applied in a sequence). The most commonly used treatment processes include coagulation/flocculation, sedimentation, filtration, and disinfection. Some water systems also use ion exchange, membrane separation, ozonation, or carbon adsorption for treatment. The basic treatment options are briefly discussed later in this chapter. As an example, Figure 1-1 depicts the water treatment process implemented by the Greater Cincinnati Water Works (GCWW) at the Miller Plant on the Ohio River.

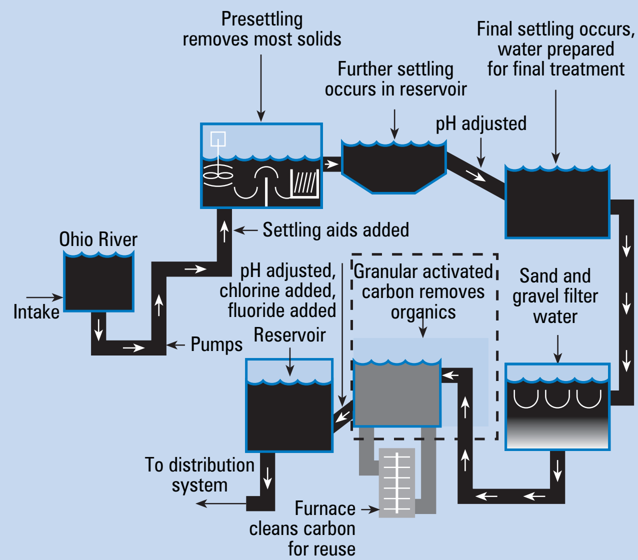


Figure 1-1. Water Treatment Process at the Miller Plant on the Ohio River (Adapted from: GCWW 2005).

Disinfection of drinking water is considered to be one of the major public health advances of the 20th century. The successful application of chlorine as a disinfectant was first demonstrated in England. In 1908, Jersey City (NJ) initiated the use of chlorine for water disinfection in the U.S. This approach subsequently spread to other locations, and soon the rates of common epidemics such as typhoid and cholera dropped dramatically. Today, disinfection is an essential part of a drinking water treatment train. Chlorine, chlorine dioxide, and chloramines are most

While disinfectants are effective in controlling many microorganisms, they can react with naturally occurring organic (and/or inorganic) matter (NOM) in the treated and/or distributed water to form potentially harmful disinfection byproducts (DBPs). Many of these DBPs are suspected of causing cancer, reproductive, and developmental problems in humans. To minimize the formation of DBPs, EPA has promulgated regulations that specify maximum residual disinfectant level goals (MRDLGs) for chlorine (4 milligrams per liter [mg/L] as chlorine), chloramines (4 mg/L as chlorine), and chlorine dioxide (0.8 mg/L as chlorine dioxide). In addition, MCLs for the DBPs total trihalomethanes (TTHMs) and haloacetic acids (HAA5) have been established as 0.080 and 0.060 mg/L, respectively. The TTHMs include chloroform, bromodichloromethane, dibromochloromethane and bromoform. The HAA5 include monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobromoacetic acid and dibromoacetic acid. In order to meet these requirements, utilities may need to remove the DBP precursor material from the water prior to disinfection by applying appropriate treatment techniques or modify their disinfection process.

often used because they are very effective disinfectants, and residual concentrations can be maintained in the water distribution system. Some utilities (in the U.S. and Europe) use ozone and chlorine dioxide as oxidizing agents for primary disinfection prior to the addition of chlorine or chlorine dioxide for residual disinfection. The Netherlands identifies ozone as the primary disinfectant, as well as common use of chlorine dioxide, but typically uses no chlorine or other disinfectant residual in the distribution system (Connell, 1998).

Prior to the passage of the SDWA of 1974, most drinking water utilities focused on meeting drinking water standards at the treatment plant, even though it had long been recognized that water quality can deteriorate in a distribution system. The SDWA introduced a number of MCLs that must be measured at various monitoring points in the distribution system. Consequently, water quality in the distribution system became a focus of regulatory action and of major interest to drinking water utilities. Subsequently, utilities worked with various research organizations (including EPA) to understand the impact of the distribution system on water quality. The collective knowledge from this research has been applied to improve the quality of water delivered to the consumer (Clark and Grayman, 1998).

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 back-flow prevention.

Some water quality goals are 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 is available. Other DBPs (HAA5) are degraded biologically when free chlorine or chloramines are nearly absent.

Prior to September 11, 2001 (9/11), few water utilities were using online monitors in a distribution system as a means of ensuring that water quality was being maintained and addressed in cases of deviation from established ranges. Now the enhanced focus on water security has led EPA and water utilities to collectively evaluate commercial technologies to remotely monitor the distribution system water quality in real-time. As a part of an evolutionary process, in the future, these monitoring technologies are expected to be integrated with computer modeling and geospatial technologies. This evolution of monitoring and modeling technologies can potentially minimize the risks from drinking water contaminants in distribution systems.

This reference guide has been prepared to provide information to drinking water utilities and researchers on the state of the art for distribution system management and modeling. Guidance is provided on the application of advanced modeling tools that can enhance a utility's ability to better manage distribution system water quality. This introductory chapter provides the basic concepts, which include:

- Distribution system – infrastructure design and operation (definitions and overview).
- Water quality problems and issues (a brief review).
- Regulatory framework (an overview).
- Assessment and management of water quality (current practices).
- Advanced tools for water quality management (in distribution systems).

Subsequent chapters will provide more details on related concepts and tools.

1.1 Distribution System - Infrastructure Design and Operation

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, 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).

1.1.1 Key Infrastructure Components

A detailed description of the various distribution system infrastructure components is readily available from other sources and beyond the scope of this document. However, for the purposes of establishing the basics, this section includes a brief discussion of the uses of the major components, their characteristics, general maintenance requirements, and desirable features.

1.1.1.1 Storage Tanks/Reservoirs

Tanks and reservoirs are used to provide storage capacity to meet fluctuations in demand, to provide reserves for fire-fighting use and other emergency situations, and to equalize pressures in the distribution system. 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. Materials of construction 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, there can be both water aging and water mixing problems. 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 document.

1.1.1.2 Pipe Network

The system of pipes or "mains" that carry water from the source (such as a treatment plant) to the consumer is often categorized as transmission/trunk, distribution, and service mains. Transmission/trunk mains usually 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, pre-stressed 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 thousands 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). Figure 1-2 depicts the various distribution system interactions that may adversely affect water quality.

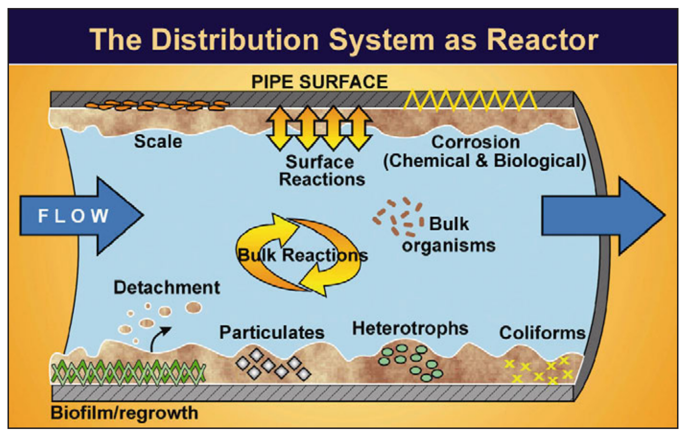


Figure 1-2. Distribution System Interactions that Affect Water Quality (Adapted from: MSU, 2005).

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.

1.1.1.3 Valves

There are two general types of valves 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-rate control valves, throttling valves, and check valves.

1.1.1.4 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 insure that they will meet their specific objectives. Pump tests are typically run every five to ten 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.

1.1.1.5 Hydrants and Other Appurtenances

Hydrants are primarily a part of the fire-fighting 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, 1998). Proper design, spacing, and maintenance are needed to insure an adequate flow to satisfy fire-fighting 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.

1.1.2 Basic Design and Operation Philosophy

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 fire fighters and are not obstacles to pedestrians and vehicles. The ready-to-serve requirements for fire fighting are governed by the National Fire Protection Association (NFPA) that establishes standards for fire-fighting capacity of distribution systems (NFPA, 2003). 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.

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

> 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 U.S. 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 (EPA 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 U.S. 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% 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 pipe every 200 years (Kirmeyer et al., 1994). Grigg, NS, 2005, provides comprehensive guidance to utilities on how to assess options for distribution system renewal. Grigg's report contains a knowledge base on condition assessment, planning and prioritization, and renewal methods.

Non-potable 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 (AwwaRF, 2002). St. Petersburg, FL, 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, D., 1996).

treatment plant and the consumer. These long travel times and low velocities may be detrimental to meeting the drinking water MCLs. Long residence times may lead to formation of DBPs, loss of disinfectant residuals, bacterial growth, and formation of biofilm.

1.1.2.1 Pipe-Network Configurations

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, there are several pathways that the water can follow from the source to the consumer. Transmission mains are typically 20 to 24 inches in diameter or larger. Dual-service mains that serve both transmission and distribution purposes are normally 12 to 20 inches in diameter. Distribution mains are usually 6 to 12 inches in diameter in every street. Service lines are typically 1 inch 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).

1.1.2.2 Multiple Source Configuration

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 due to 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.

1.1.2.3 Impact of System Design and Operation on Water Quality

Based on the design and configuration of a particular system, there are many opportunities for water quality to change as water moves between the treatment plant and the consumer. These unwanted changes may occur due to 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 bio-deterioration of materials (Water Research Centre, 1976). 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).

It is difficult and expensive to study the problems caused by system design and configuration in full-scale systems. For example, one approach to studying residual chlorine levels in dead-end or low-flow situations would be to construct a pilot-scale pipe system to simulate the phenomena. Another approach would be to use mathematical hydraulic and water quality models for simulation. For either of these approaches to work, they must be properly configured and/or calibrated to closely simulate a full-scale system. A combination of these approaches may be used to assess various operational and design decisions, to determine the impacts resulting from the inadvertent or deliberate introduction of a contaminant into the distribution system, and to assist in the design of systems to improve water quality.

In pipes, it has been found that chlorine can be lost through both the interaction with NOM in the bulk phase and with pipe walls themselves in transporting finished water. This mechanism for loss of chlorine may be even more serious than long residence times in tanks. The pipe wall demand, possibly due to biofilm and tubercles, may use up the chlorine very rapidly in a distribution system. Maintaining adequate levels of disinfectant residual may require routine cleaning/ replacement of pipes and intensive treatment (Clark et al., 1993a).

1.2 Water Quality Problems and Issues

Drinking water treatment in the U. S. has played a major role in reducing waterborne disease. For example, the typhoid death rate for a particular year in the 1880s was 158 per 100,000 in Pittsburgh, PA, compared with 5 per 100,000 in 1935. Such dramatic reductions in waterborne disease outbreaks were brought about by the application of drinking water standards and engineering "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. The residual disinfectant levels served to protect the water quality within the distribution system prior to its delivery to the consumer (Clark et al., 1991b).

Despite the passage of the SDWA, waterborne outbreaks still occur. Two extensively studied examples of waterborne disease in the U.S. were an *Escherichia coli O157:H7 (E. coli)* outbreak in Cabool, Missouri, in 1989 and a *Salmonella* outbreak in Gideon, Missouri, in 1993. These two examples, discussed later in Chapter 7, illustrate the importance of the multiple-barrier concept. In both cases, the water source was un-disinfected groundwater and the utility's infrastructure was breached, allowing contaminants to enter the system. This contamination resulted in major waterborne outbreaks. Water quality modeling was used in both cases to identify the source of the outbreaks and to study the propagation of the outbreak through the distribution network (Clark et al., 1993a and b).

One useful outcome of the outbreaks in Missouri is that the ensuing investigative studies have typically led to the development and enhancement of scientific analysis techniques. For example, the Gideon *Salmonella* outbreak conclusions were based on statistical studies performed by Centers for Disease Control and Prevention (CDC) and corroborated by water quality modeling performed by EPA. The study provides an example of how tools such as water quality models can be used to reliably study contaminant propagation in a distribution system (Clark et al., 1996). Both the Gideon and Cabool incidents were associated with source water contamination, inadequate treatment, and breeches in the distribution system.

These types of problems are not just isolated incidents of infrastructure breakdowns. In fact, several problems with drinking water systems in the U. S. have been identified by researchers. The National Research Council (NRC, 2005) examined the causes of waterborne outbreaks reported by various investigators between 1971 and 2004. Figure 1-3 presents the total number and proportion of waterborne diseases associated with distribution system deficiencies

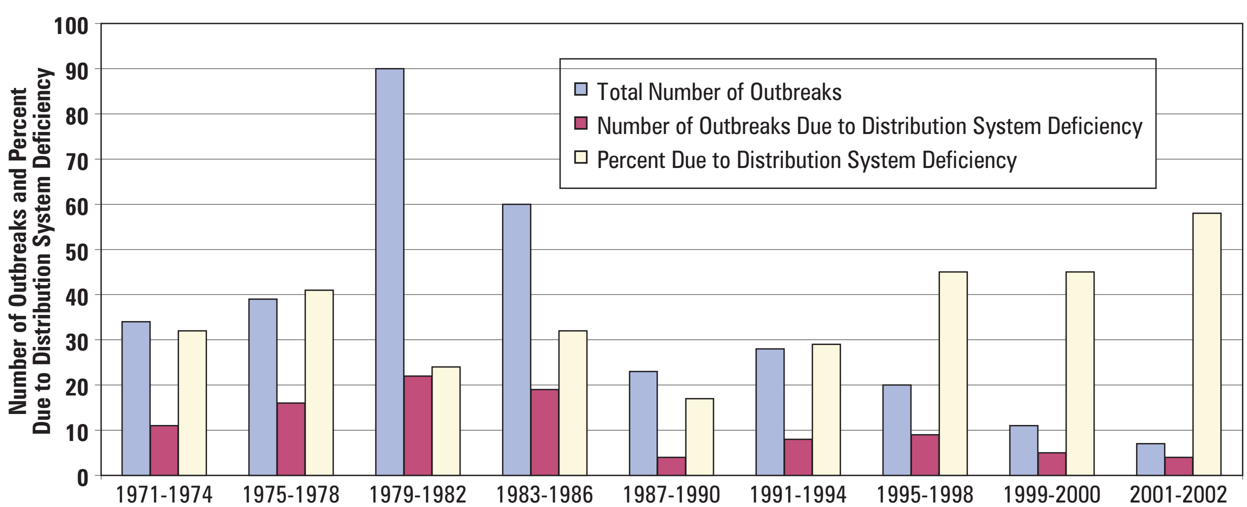


Figure 1-3. Total Number and Proportion of U.S. Waterborne Diseases Associated with Water Distribution System Deficiencies.

On December 16, 1974, the U. S. Congress passed the SDWA, which authorized the EPA to promulgate 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 MCLs for 10 inorganic contaminants, six 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.

(extracted from the NRC report). As the figure reveals, overall there is a general decrease in the total number of waterborne disease outbreaks during the reported period. However, there is a general increase in the percentage of outbreaks that are associated with distribution system deficiencies. The NRC report attributes this increase in percentage of outbreaks (attributable to distribution system deficiencies) to the lack of historical regulatory focus on distribution systems.

1.3 Regulatory Framework

Concerns about waterborne disease and uncontrolled water pollution resulted in federal water quality legislation starting in 1893 with the passage of the Interstate Quarantine Act and continuing to 1970 under the stewardship of the U.S. Public Health Service (AWWA, 1999). Even though significant advances were made to eliminate waterborne disease outbreaks during that period, the focus of drinking water concerns began to change with the formation of the EPA in late 1970. 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 SDWA of 1974 was a reflection of concerns about chemical contamination. In this section, a brief overview of the regulatory framework is presented. A detailed history of the evolution of the federal drinking water regulations is beyond the scope of this document.

Early in the history of the SDWA, the major focus of EPA was to implement the Act and to initiate the regulatory process. The first MCL established under the SDWA was the TTHM Rule in 1979. However, after several years of developing regulations, it became obvious that the rulemaking process must extend beyond a focus on MCLs at the treatment plant and into the distribution system. Many water utilities in the U.S. using surface supplies were experiencing waterborne outbreaks, especially from *Giardia*. The 1986 SDWA Amendments laid the groundwork for the promulgation of the Total Coliform Rule (TCR) and the Surface Water Treatment Rule (SWTR) in 1989. The 1986 SDWA Amendments also set forth an aggressive plan to eliminate lead from PWSs and resulted in the promulgation of the Lead and Copper Rule (LCR) in 1991. These actions therefore extended the SDWA beyond its focus on the treatment plant and into the distribution system (Owens, 2001).

A summary of the evolution of federal drinking water regulation since the passage of the SDWA in 1974 is presented in Figure 1-4. 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 Clinton issued Presidential Decision Directive (PDD) 63 that outlined a policy on critical infrastructure protection, including our nation's water supplies. However, it was not until after September 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 PWSs that supply water to the same population throughout the year.

Table 1-1 summarizes the key requirements of the regulations presented in Figure 1-4 from a distribution system compliance perspective.

Many of the tools and techniques discussed in this reference guide can assist in complying with the rules and regulations and security issues discussed above. Water quality modeling techniques can be used to identify points in the distribution system that experience long retention times, which can in turn represent locations in the system that may experience chlorine residual loss, excessive formation of DBPs, and the formation of biofilms. Chlorine residual loss, in conjunction with biofilm

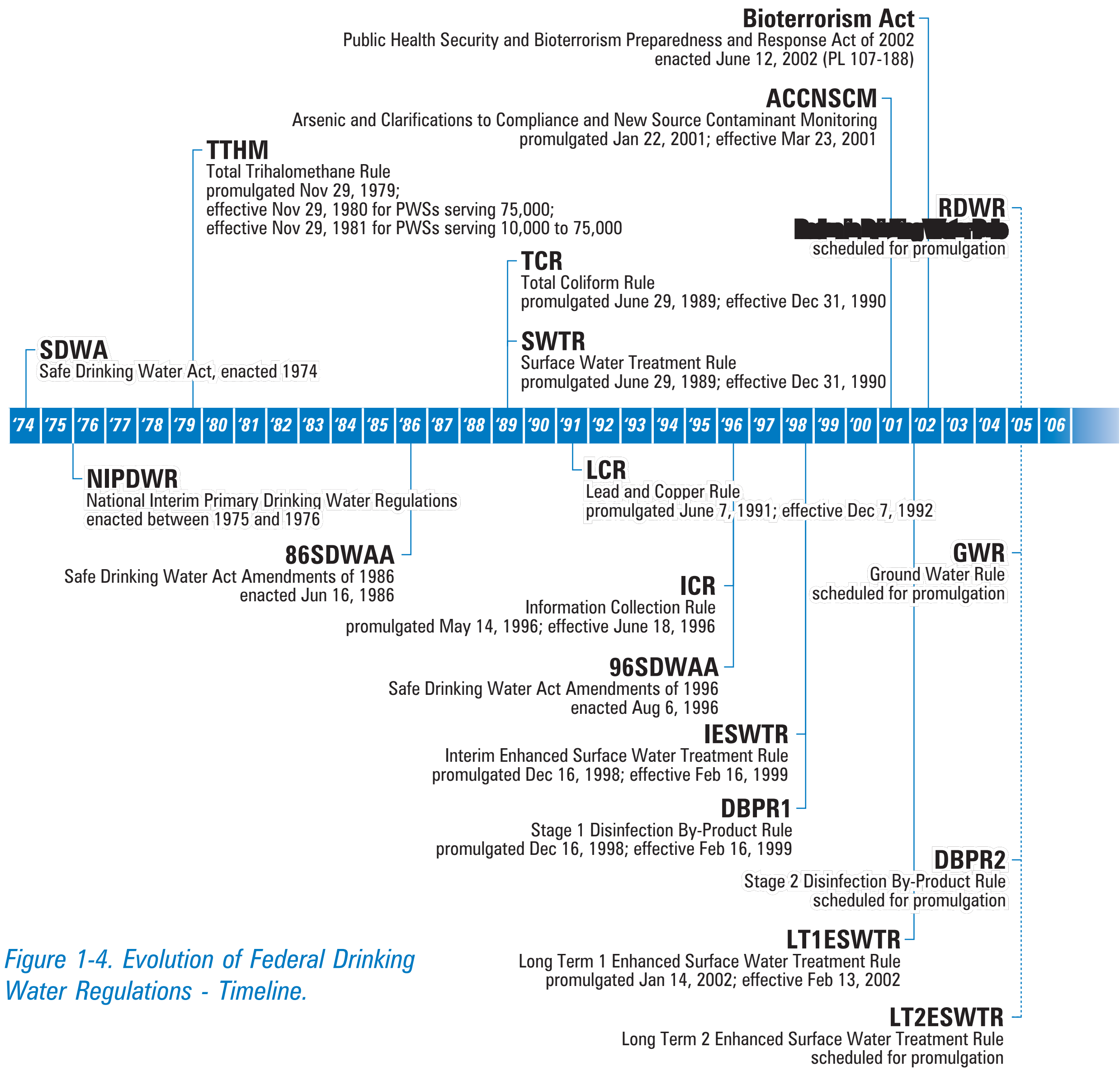


Figure 1-4. Evolution of Federal Drinking Water Regulations - Timeline.

Meeting and balancing the requirements of the various regulations can provide a significant challenge to water utilities. In some cases, regulations provide guidance or requirements that could result in contradictory actions. For example, the SWTR requires the use of chlorine or some other disinfectant. However, chlorine or other disinfectants interact with NOM in treated water to form DBPs. Similarly, raising the pH of treated water will assist in controlling corrosion but may increase the formation of TTHMs. Various analytical tools, such as water quality models, can provide the utility with information and an understanding that helps the utility in balancing the contradictory requirements of some regulations.

formation, may result in the sporadic occurrence of coliforms ("indicator" organisms associated with bacteriologically polluted water). Models can be used to define mixing zones where blending water from two or more sources results in water quality problems. Specifically, water quality modeling tools may assist utilities in complying with the TCR, SWTR, IESWTR, LT1ESWTR, and LCR. Modeling can assist in identifying parts of the system with high TTHM formation potential (DBPR1) and meeting the Initial Distribution System Evaluation (IDSE) requirements of the DBPR2 (see the IDSE Case Study in Chapter 7). In addition, modeling techniques can assist in tracking contamination from cross-connections and other accidental or deliberate contamination events such as a waterborne outbreak.

1.4 Assessment and Management of Water Quality

Water utilities treat nearly 34 billion gallons of water every day (EPA, 1999). Generally, surface water systems require more treatment than groundwater

Table 1-1. Selected Rules and Regulations Dealing with Distribution Systems (Not Inclusive)

Regulation	Key Distribution System Requirements
SDWA	Gives EPA the authority to establish national primary and secondary drinking water regulations (MCLs and MCLGs).
NIPDWR	The NIPDWR which was adopted at the passage of the SDWA required that representative coliform samples be collected throughout the distribution system.
TTHM	Established a standard for TTHMs as 0.1 mg/L.
86SDWAA	Established the MCLG concept.
TCR	Regulates coliform bacteria which are used as surrogate organisms to indicate whether or not treatment is effective and system contamination is occurring.
SWTR	Requires using chlorine or some other disinfectant.
LCR	Monitoring for compliance with the LCR is based entirely on samples taken at the consumer's tap.
ICR	Provided data to support the interim and long-term enhanced SWTR, and Stage 2 DBP rule.
96SDWAA	Has many provisions dealing with distribution systems, including the role that surface water quality can play in influencing the quality of distributed water.
IESWTR	Provisions to enhance protection from pathogens, including *Cryptosporidium*, and intended to prevent increases in microbial risk while large systems comply with the DBPR1.
DBPR1	Has lowered the standard for TTHMs from 0.1 mg/L to 0.08 mg/L. This standard applies to all community water supplies in the U. S. and requires monitoring and compliance at selected points in the distribution system.
LT1ESWTR	Provisions to enhance protection from pathogens, including *Cryptosporidium*, and prevent increases in microbial risk for systems serving less than 10,000 people while they comply with the DBPR1.

systems because they are directly exposed to the atmosphere, runoff from rain and melting snow, and other industrial sources of contamination. Water utilities use a variety of treatment processes to remove contaminants from drinking water prior to distribution. The selected treatment combination is based on the contaminants found in the source water of that particular system. The general techniques include:

- Coagulation/Flocculation: This process removes dirt and other particles suspended in the water. In this process, alum, iron salts, and/or synthetic organic polymers are added to the water to form sticky particles called "floc," which attract the suspended particles.

- Sedimentation: In this process, the flocculated particles are gravity-settled and removed from the water.

- Filtration: Many water treatment facilities use filtration to remove the smaller particles from the water. These particles include: clays and silts, natural organic matter, precipitates from other treatment processes in the facility, iron and manganese, and microorganisms. Filtration clarifies the water and enhances the effectiveness of disinfection.

- Disinfection: Water is disinfected at the water treatment plant (or at the entry to the distribution system) to ensure that microbial contaminants are inactivated. Secondary disinfection is practiced in order to maintain a residual in the distribution system.

Once the treated water enters the distribution system, a number of processes may occur that can adversely impact the water quality delivered to consumers. As the water enters a network of buried pipes, valves, joints, meters, and service lines, it is subject to disruptions such as water hammer (transient pressure shock wave), aging (at dead ends and large tanks), corrosion, cross-connections, leaching of toxic chemicals, intrusion of pathogens, and pipeline breaks. Some of these events may be regular occurrences, such as water aging, loss of chlorine residual in dead ends, or deposition of sedimentation in stagnant areas. Others may be rare or unusual events. Any of these events can cause the water quality to deteriorate and pose a potential public health risk. Some routine distribution system design changes and maintenance or operational procedures that can help to prevent or reduce the effects of such events include the following:

- Tank Mixing: Inadequate mixing in a tank can lead to stagnant areas containing older water

Maintaining water quality in a drinking water distribution system while assuring adequate disinfection and reducing DBPs is a significant challenge for many drinking water utilities. This challenge will be even greater under the more stringent requirements of the LT2ESWTR and the DBPR2. Utilities that use chorine as their primary disinfectant and that have elevated organic levels in their treated water, long detention times, and/or warm water may have difficulty in meeting these regulations. The Las Vegas Valley Water District is conducting research to explore the feasibility of employing "targeted" distribution system treatment systems. This type of targeted system (or systems) would utilize small-scale water treatment technology to reduce the concentration of disinfection byproducts in those areas that might exceed the SDWA MCLs established under the LT2ESWTR and DBPR2. These systems are intended to be designed and operated in conjunction with a water quality/hydraulic model which would be used to predict where these decentralized treatment systems should be located. If the treatment technology is relatively mobile, it could be moved based on model predictions to locations where MCL violations are likely to occur. In addition, these types of systems would be valuable should a security threat arise.

that has lost its disinfectant residual. Changes in operations (e.g., exercising the tank) or modifications to inlet-outlet configurations can improve mixing.

- Re-chlorination: Some parts of a distribution system may experience long travel times from the treatment plant resulting in loss of chlorine residual. Installation of booster chlorination facilities at these locations can sometimes be an effective means of insuring an adequate residual in these areas.
- Conventional Flushing: This procedure generally involves opening hydrants in an area until the water visibly runs clear. The object of this action would be to quickly remove contaminated water; however, it would not likely be effective in removal of contaminants that become attached to the pipe surfaces. Flushing only provides a short-term remedy.
- Unidirectional Flushing: This procedure involves the closure of valves and opening of hydrants to concentrate the flow in a limited number of pipes. Flow velocities are maximized so that shear velocity near the pipe wall is maximized. It is intended to be done in a progressive fashion, proceeding outward from the source of water in the system so that flushing water is drawn from previously flushed

Federal and state drinking water regulations are designed to provide a water supply to consumers that meets minimum health-based requirements. However, water utilities may choose to implement programs that go beyond current federal, state, and local regulatory requirements to increase the water quality and reduce the potential for contamination in water systems. There are several methods and guidelines that have been designed to assist utilities in providing water of a quality that exceeds the minimum requirements. These methods include: Hazard Analysis Critical Control Point (HACCP), source water optimization, and distribution system water quality optimization plans (DSOP).

DSOP is one example of a framework for evaluating and improving programs that affect distribution system water quality (Friedman et al., 2005). Aspects of the DSOP include evaluation of conditions within the distribution system, creation of improved documentation, and enhancement of communication between the various utility functions that impact water quality in the distribution system. DSOPs address both regulatory/compliance issues and customer issues related to aesthetic properties of drinking water. The DSOP approach was piloted at three water utilities and a general template was developed that can be used by small, medium, and large utilities. The following ten steps are identified as part of the development of a DSOP:

1. Formation of a committee to discuss distribution system issues of interest/concern and to guide the process of DSOP development.
2. Identification of water quality and operating goals.
3. Completion of a distribution system audit.
4. Comparison of audit results to industry best management practices.
5. Development of a list of utility needs for optimizing distribution system water quality.
6. Prioritization of DSOP elements based on relative contribution towards improving water quality and precluding water quality degradation or contamination.
7. For each priority DSOP element, compilation of applicable standard operating procedures (SOPs) and ongoing programs that provide information related to the condition of the distribution system and water quality.
8. Development and implementation of priority programs.
9. Periodic review of programs and goals developed as part of the DSOP.
10. Development of revised SOPs that describe the optimized approach.

DSOP and other aforementioned methodologies are still in their early stages of application in the water supply industry and will require further evaluation to determine their effectiveness in meeting the goals to improve water quality in drinking water systems.

reaches. No special equipment is required; however, some planning time is required to determine the flushing zones, the valves and hydrants to be operated, and the duration of the flushing exercise for each zone.

- Valve Exercising Program: A routine program to exercise isolation valves can have several positive effects. These include identifying (and repairing) malfunctioning valves and identifying valves that are in an inappropriate setting (e.g., closed valves that are expected to be open).
- Cross-Connection Control Program: An inspection program intended to ensure no interconnection(s) between the drinking water and wastewater systems in homes and buildings.

Examples of routine maintenance and operation procedures for pipe cleaning include the following (AwwaRF, 2004):

- Air Scouring, Swabbing and Abrasive pigging: Air scouring, swabbing, and abrasive pigging are progressively more aggressive cleanup techniques that involve more specialized equipment and skills. A few water utilities have implemented these methods using their own staff; typically, these methods are contracted to specialty firms. Implementation of these methods would require installation of new pipeline appurtenances (e.g., pig launching and receiving stations; pigging is not recommended for cast iron pipes).
- Chemical/Mechanical Cleaning and Lining: Chemical cleaning involves the recirculation in an isolated pipe section of proprietary acids and surfactants to remove scale and deposits, while mechanical cleaning is accomplished by dragged scrapers. These techniques are typically applied in the rehabilitation of older unlined cast iron pipe which, over time, have become scaled and tuberculated. These cleaning operations are typically followed by an in-situ application of a thin cement mortar or epoxy lining to ensure lasting protection.

If the symptoms persist after the application of these techniques, the pipes are usually replaced.

1.5 Advanced Tools for Water Quality Management

Recent advancements in computation and instrumentation technologies have led to the availability of advanced tools that are already beginning to improve a utility's ability to effectively manage water quality in distribution systems. These computational advancements have led to the development of software models that can simulate the behavior of distribution system networks. Water distribution system models (such as EPANET) have become widely accepted both within the water utility industry and the general research arena for simulating both hydraulic and water quality behavior in water distribution systems. The advancements in instrumentation and Supervisory Control and Data Acquisition (SCADA) systems now enable the utilities to monitor and control various water quality parameters from a remote location in real-time within a distribution system network. Furthermore, recent advances in Geographic Information Systems (GIS) technology have led to the integration of remote monitoring network models with GIS layers. This combination provides utilities a visual tool to efficiently manage both water quality and distribution system assets such as pipes, pumps, and valves.

1.6 Report Organization

Various chapters of this reference guide will describe modeling and monitoring tools for effectively managing water quality in drinking water distribution systems. Examples and protocols for effectively applying water quality models for understanding and resolving water quality issues in networks will be presented. Another important aspect of effectively applying water quality models is to ensure that they are properly and periodically calibrated. Tracer tests are one of the most effective techniques for calibrating a water quality model. Modeling techniques, when combined with advanced monitoring and geospatial technologies, can play a vital role in managing water quality in distribution systems. Chapter 2 provides an overview on modeling of distribution systems for water quality. Chapter 3 describes techniques for conducting tracer studies in distribution systems. Chapter 4 presents data analysis techniques for effectively calibrating a distribution system model using tracer or other field data. Chapter 5 provides an overview of monitoring techniques and technologies available for monitoring water quality. Chapter 6 introduces geospatial technology and its relation to water distribution systems. Finally, Chapter 7 is a compilation of real-world applications of water quality modeling and monitoring for planning, analysis and simulation of historical events.

1.7 Summary

Distribution system infrastructure is a major asset of most water utilities. It serves many important functions in a community, such as promoting eco-

The information presented in this reference guide is intended for a general technical audience. The various chapters provide an overview of the state-of-art techniques for managing water quality in distribution systems. For a more comprehensive case-specific solution, the reader should refer to text books in specific subject areas and/or consult with water quality professionals. The following is a brief listing of recommended books (listed in alphabetical order by title):

1. Advanced Water Distribution Modeling and Management. T.M. Walski, D.V. Chase, D.A. Savic, W. Grayman, S. Beckwith, and E. Koelle. Haestad Press, Waterbury, CT. 2003.
2. Comprehensive Water Distribution Systems Analysis Handbook. P.B. Boulos, K.E. Lansey, and B.W. Karney. MWHSOFT, Inc., Pasadena, CA. 2004.
3. Computer Modeling of Water Distribution Systems (M32), AWWA. 2004.
4. GIS Applications for Water, Wastewater, and Stormwater Systems. U. Shamsi. CRC Press. 2005.
5. Hydraulics of Pipeline Systems. B.E. Larock, R.W. Jeppson, G.Z. Watters. CRC Press. 1999.
6. Microbial Quality of Water Supply in Distribution Systems. Edwin E. Geldreich. CRC Press. 1996
7. Modeling, Analysis and Design of Water Distribution Systems. L. Cesario. AWWA. 1995.
8. Modeling Water Quality in Drinking Water Distribution Systems. R.M. Clark and W.M. Grayman. AWWA. 1998.
9. Online Monitoring for Drinking Water Utilities. Edited by E. Hargesheimer, O. Conio, and J. Popovicova. AwwaRF – CRS ProAqua. 2002.
10. Safe Drinking Water: Lessons from Recent Outbreaks in Affluent Nations. S.E. Hrudey and E.J. Hrudey, IWA Publishing. 2004.
11. Water Distribution Systems Handbook. Edited by L.W. Mays, McGraw Hill. 2000.
12. Water Supply Systems Security. Edited by L.W. Mays, McGraw Hill. 2004.

nomic growth, supporting public safety, and protecting public health. In order for a community to grow and prosper, it must have the physical infrastructure to provide basic services such as water supply. In addition to the economic implications of adequate water supply, water systems play a critical role in supporting public safety through the provision of fire protection capacity. Frequently, insurance rates in a community are tied to the fire protection capability of the water system. Water systems play a key role in protecting a community's public health by providing safe drinking water to water consumers.

References

American Society of Civil Engineers (ASCE). "Report Card for America's Infrastructure, Drinking Water." ASCE, Reston, VA. 2005.

American Water Works Association (AWWA). *AWWA Manual M31, Distribution System Requirements for Fire Protection*, AWWA, Denver, CO. 1998.

AWWA. *Water Quality & Treatment – A Handbook of Community Water Supplies.* Edited by R.D. Letterman, McGraw-Hill, NY. 1999.

American Water Works Association Research Foundation (AwwaRF). *Standard Operating Procedures for Decontamination of Water Infrastructure.* March, 2004.

AwwaRF. *Impacts of Fire Flow on Distribution System Water Quality, Design, and Operation.* 2002.

Camper, A.K., K. Brastrup, A. Sandvig, J. Clement, C. Spencer, and A.J. Capuzzi. "Impact of distribution system materials on bacterial regrowth." *Journal of AWWA,* 95(7):107-121. 2003.

Clark, R.M., W.M. Grayman, and R.M. Males. "Contaminant Propagation in Distribution Systems," *Journal of Environmental Engineering*, ASCE, 114:(2). 1988.

Clark, R.M., W.M. Grayman, and J.A. Goodrich. "Water Quality Modeling: Its Regulatory Implications." Proceedings, AwwaRF/EPA Conference on Water Quality Modeling in Distribution Systems, Cincinnati, OH. 1991a.

Clark, R.M., D.J. Ehreth, and J.J. Convery. "Water Legislation in the US: An Overview of the Safe Drinking Water Act," *Toxicology and Industrial Health*, 7(516):43-52. 1991b.

Clark, R.M., and W.A. Feige. "Meeting the Requirements of the Safe Drinking Water Act," in *Strategies and Technologies for Meeting the Requirements of the SDWA.* Edited by Robert M. Clark and R. Scott Summers, Technomics, Publishing Company, Inc., Lancaster, PA. 1993.

Clark, R.M., W.M. Grayman, R.M. Males, and A.F. Hess, 1993a. "Modeling Contaminant Propagation in Drinking Water Distribution Systems," *Journal of Environmental Engineering*, ASCE, 119(2):349-364. 1993.

Clark, R.M., J.A. Goodrich, and L.J. Wymer. "Effect of the Distribution System on Drinking Water Quality," *Journal of Water Supply Research and Technology - Aqua*, 42(1):30-38. 1993b.

Clark, R.M., E.E. Geldreich, K.R. Fox, E.W. Rice, C.H. Johnson, J.A. Goodrich, J.A. Barnick, and F. Abdesaken. "Tracking a *Salmonella* serovar Typhimurium Outbreak in Gideon, Missouri: Role of Contaminant Propagation Modeling," *Journal of Water Supply Research and Technology - Aqua*, 45(4):171-183. 1996.

Clark, R.M., and W.M. Grayman. *Modeling Water Quality in Drinking Water Distribution Systems.* AWWA, Denver, CO. 1998.

Clark, R.M., W.M. Grayman, S.G. Buchberger, Y. Lee, and D.J. Hartman. "Drinking Water Distribution Systems: An Overview," in *Water Supply Systems Security*. Edited by Larry W. Mays, McGraw-Hill, NY. pp 4.1- 4.49. 2004

Clark, R.M., and D. L. Tippen. "Water Supply" in *Standard Handbook of Environmental Engineering.* Edited by Robert A. Corbitt, McGraw-Hill, NY. pp 5.173-5.220. 1990.

Connell, G.F. "European Water Disinfection Practices Parallel U.S. Treatment Methods," *Drinking Water and Health Quarterly*. August 1, 1998. http://www.clo2.com/reading/waternews/european.html

EPA. *The Clean Water and Drinking Water Infrastructure Gap Analysis.* EPA - Office of Water, Washington DC. September 2002.

EPA. *25 Years of the Safe Drinking Water Act: History & Trends.* EPA 816-R-99-007. December 1999.

Fair, G.M., and J.C. Geyer. "Water Supply and Waste-Water Disposal," John Wiley and Sons, Inc., NY. 1971.

Friedman, M., G. Kirmeyer, G. Pierson, S. Harrison, K. Martel, A. Sandvig, and A. Hanson. *Development of Distribution System Water Quality Optimization Plans.* AwwaRF/AWWA. Denver, CO. 2005.

Geldreich, E.E., H.D. Nash, D.J. Reasoner, and R.H. Taylor. "The Necessity of Controlling Bacterial Populations in Potable Water: Community Water Supply," *Journal of AWWA,* 64:596-602. 1972.

Greater Cincinnati Water Works. "Water Treatment," http://www.cincinnati-oh.gov/water/pages/-3283-/. 2005.

Grigg, NS. *Assessment and Renewal of Water Distribution Systems.* AwwaRF Report # 91025F, June 2005.

Gullick, R.W., W.M. Grayman, R.A. Deininger, and R.M. Males. "Design of Early Warning Monitoring Systems for Source Waters," *Journal of AWWA*, 95(11):58-72. 2003.

Insurance Services Office (ISO). *Fire Suppression Rating Schedule.* Insurance Services Office, NY. 2003.

International Life Sciences Institute. *Early Warning Monitoring to Detect Hazardous Events in Water Supplies.* Edited by T.M. Brosnan, Washington, D.C. 1999.

Kirmeyer, G.J., W. Richards, and C. Dery-Smith. *An Assessment of Water Distribution Systems and Associated Needs*. AwwaRF. 1994.

LeChevallier, M.W., T.M. Babcock, and R.G. Lee. "Examination and Characterization of Distribution System Biofilms," *Applied and Environmental Microbiology*, 53:2714-2724. 1987.

Maul, A., A.H. El-Shaarawi, and J.C. Block. "Heterotrophic Bacteria in Water Distribution Systems - I. Spatial and Temporal Variation." *The Science of the Total Environment*, 44:201-214. 1985a.

Maul, A., A.H. El-Shaarawi, and J.C. Block. "Heterotrophic Bacteria in Water Distribution Systems - II. Sampling Design for Monitoring." *The Science of the Total Environment*, 44:215-224. 1985b.

Montana State University (MSU) Center for Biofilm Engineering. Image provided by Pat Dirckx. 2005.

National Fire Protection Association (NFPA). *Fire Protection Handbook, 19th edition.* Edited by A.E. Cote, National Fire Protection Association, Quincy, MA. 2003.

NRC. *Public Water Supply Distribution Systems: Assessing and Reducing Risks – First Report.* The National Academies Press, Washington, DC. 2005.

Okun, D. "Distributing reclaimed water through dual systems," *Journal of AWWA,* 89 (11), pp. 52-64. 1996.

Owens, J. *A Review of Federal Drinking Water Regulations in the U.S., in Controlling Disinfection By-Products and Microbial Contaminants in Drinking Water.* Edited by Robert M. Clark and Brenda Boutin, EPA-600-R-01-110. pp 2-1 to 2-14. December 2001.

PDD 63. *Critical Infrastructure Protection*. The White House, Washington D.C. May 22, 1998.

PL107-188. Public Health Security and Bioterrorism Preparedness and Response Act of 2002.

Safe Drinking Water Act (SDWA), 1974, Public Law 93-523.

Walski, T. M, D.V. Chase, D.A. Savic, W.M. Grayman, S. Beckwith, and E. Koelle. *Advanced Water Distribution Modeling and Management.* Haestad Press, Waterbury, CT. pp 1-4. 2003.

Water Research Centre. "Deterioration of Bacteriological Quality of Water During Distribution," Notes on Water Research No. 6. 1976.

Zhang, W., and F.A. DiGiano. "Comparison of Bacterial Regrowth in Distribution Systems Using Free Chlorine and Chloramine: A Statistical Study of Causative Factors." *Water Research*, 36:6:1469-1482. 2002.

Chapter 2
Modeling Water Quality in Drinking Water Distribution Systems

This chapter covers the use of models to simulate the flow and water quality conditions in a distribution system network. Models are mathematical or physical approximations of a real-world system and can be used to study the behavior of actual system(s). A variety of computer software modeling tools are now available to perform these simulations. These tools are now commonly used by trained engineers and scientists to study and improve water distribution system network design and operation.

Water distribution system models have become widely accepted within the water utility industry as a mechanism for simulating the hydraulic and water quality behavior in water distribution system networks. Current water distribution modeling software is powerful, sophisticated and user-friendly. Many software packages are integrated with GIS and Computer Aided Design (CAD) technology in order to facilitate model construction and storage and display of model results. Early network models simulated only steady-state hydraulic behavior. In the 1970s, modeling capability was expanded to include Extended Period Simulation (EPS) models that could accommodate time-varying demand and operations. Subsequently, in the early 1980s, investigators began introducing the concept of water quality modeling. Most water distribution system modeling software packages now routinely incorporate water quality simulation capability. More recently, transient models for simulating water hammer (a transient phenomenon) and tank mixing/aging models have either been incorporated into or integrated with water distribution system models. Algorithms have been developed that enable users to optimize water system design and operation, assist in model calibration, and perform probabilistic analyses. Each of these model types are briefly described later in this chapter.

Water distribution system models are more commonly being used to replicate the behavior of a real or proposed system for a variety of purposes including: capital investment decisions, development of master plans, estimation of fire protection capacity, design of new systems and extension or rehabilitation of existing systems, energy management, water quality studies, various event simulations and analysis, optimal placement of sensors, and daily operations. The costs associated with constructing and maintaining a distribution system model may be more easily justified if it is used for a variety of applications by a water utility (Grayman, 2000).

2.1 Distribution System Network Hydraulic Modeling

The network hydraulic model provides the foundation for modeling water quality in distribution systems. This subsection provides a brief history of hydraulic modeling, an overview of theoretical concepts, basic model inputs, and general criteria for selection and application.

2.1.1 History of Hydraulic Modeling

Hardy Cross first proposed the use of mathematical methods for calculating flows in complex networks (Cross, 1936). This manual, iterative procedure was used throughout the water industry for almost 40 years. With the advent of computers and computer-based modeling, improved solution methods were developed for utilizing the Hardy Cross methodology. The improved implementations of this method were in widespread use by the 1980s (Wood, 1980a).

Also, in the early 1980s, the concept of modeling water quality in distribution system networks was developed based on steady-state formulations (Clark et al., 1986). By the mid-1980s, water quality models were developed that incorporated the dynamic behavior of water networks (Grayman et al., 1988). The usability of these models was greatly improved in the 1990s with the introduction of the public domain EPANET model (Rossman, 2000) and other Windows-based commercial water distribution system models.

Initially, hydraulic models simulated flow and pressures in a distribution system under steady-state conditions where all demands and operations remained constant. Since system demands (and consequently the flows in the water distribution network) vary over the course of a day, EPS models were developed to simulate distribution system behavior under time-varying demand and operational conditions. These models have now become ubiquitous within the water industry and are an integral part of most water system design, master planning, and fire flow analyses.

2.1.2 Overview of Theoretical Concepts

The theory and application of hydraulic models is thoroughly explained in many widely available references (Walski et al., 2003; American Water Works Association, 2004; Larock et al., 2000). Essentially, three basic relations are used to calculate fluid flow in a pipe network. These relationships are:

- Conservation of Mass: This principle requires that the sum of the mass flows in all pipes entering a junction must equal the sum of all mass flows leaving the junction. Because water is essentially an incompressible fluid, conservation of mass is equivalent to conservation of volume.
- Conservation of Energy: There are three types of energy in a hydraulic system: kinetic energy associated with the movement of the fluid, potential energy associated with the elevation, and pressure energy. In water distribution networks, energy is referred to as "head" and energy losses (or headlosses) within a network are associated primarily with friction along pipe walls and turbulence.
- Pipe Friction Headloss: A key factor in evaluating the flow through pipe networks is the ability to calculate friction headloss (Jeppson, 1976). Three empirical equations commonly used are the Darcy-Weisbach, the Hazen-Williams, and the Manning equations. All three equations relate head or friction loss in pipes to the velocity, length of pipe, pipe diameter, and pipe roughness. A fundamental relationship that is important for hydraulic analysis is the Reynolds number, which is a function of the kinematic viscosity of water (resistance to flow), velocity, and pipe diameter. The most widely used headloss equation in the U.S. is the Hazen-Williams equation. Though the Darcy Weisbach equation is generally considered to be theoretically more rigorous, the differences between the use of these two equations is typically insignificant under most circumstances.

A distribution system is represented in a hydraulic model as a series of links and nodes. Links represent pipes whereas nodes represent junctions, sources,

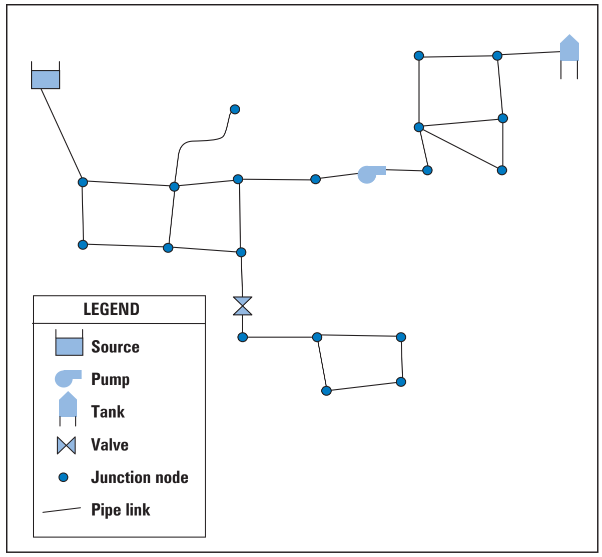


Figure 2-1. Simple Link-Node Representation of a Water Distribution System.

tanks, and reservoirs. Valves and pumps are represented as either nodes or links depending on the specific software package. Figure 2-1 illustrates a simple link-node representation of a water distribution system.

As mentioned previously, there are two types of analyses that may be conducted on drinking water distribution systems: steady-state and EPS. In a steady-state analysis, all demands and operations are treated as constant over time and a single solution is generated. In the EPS mode, variations in demand, tank water levels, and other operational conditions are simulated by a series of steady-state analyses that are linked together. Each steady-state solution in the EPS mode involves a separate solution of the set of non-linear equations. EPS is used as the basis for

Hydraulic models represent the basic underlying equations (conservation of mass and conservation of energy) as a series of linear and non-linear equations. Because of the non-linearity, iterative solution methods are commonly used to numerically solve the set of equations. The most common numerical method utilized is the Newton-Raphson method.

Conservation of Mass: The conservation of mass principle for hydraulic analysis requires that the sum of the mass flow in all pipes entering a junction must equal the sum of all mass flows leaving the junction. In EPS, if storage is involved, a term for describing the accumulation of water at those nodes is included. Mathematically, the principle can be represented as follows:

$$\sum_{i=1}^{n} (Q_i - U_i) - \frac{dS}{dt} = 0 \quad \text{(Equation 2-1)}$$

where

Q_i = inflow to node in i-th pipe in ft^3/sec (m^3/sec)

U_i = water used or leaving at the i-th node in ft^3/sec (m^3/sec)

$\frac{dS}{dt}$ = change in storage in ft^3/sec (m^3/sec) water quality modeling. Though the EPS solution does introduce some approximations and ignores the transient phenomena resulting from sudden changes (e.g., a pump being turned on), these more refined assumptions are generally not considered significant for most distribution system studies.

Conservation of Energy: The conservation of energy principle requires that the difference in energy between two points in a network must be the same regardless of flow path. For hydraulic analysis, this principle can be represented in terms of head as follows:

$$Z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} + \sum h_P = Z_2 + \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + \sum h_L + \sum h_M \quad \text{(Equation 2-2)}$$

where

$Z_{1\text{ and }2}$ = elevation at points 1 and 2, respectively, in ft (m)

$P_{1\text{ and }2}$ = pressure at points 1 and 2, respectively, in lb/ft^2 (N/m^2)

γ = fluid (water) specific weight, in lb/ft^3 (N/m^3)

$V_{1\text{ and }2}$ = velocity at points 1 and 2, respectively, in ft/s (m/s)

g = acceleration due to gravity, in ft/sec^2 (m/sec^2)

h_P = pumping head gain, in ft (m)

h_L = head loss in pipes, in ft (m)

h_M = head loss due to minor losses, in ft (m)

Pipe-friction headloss: The equation most commonly used in modeling software for computation of pipe-friction headloss is the Hazen-Williams equation represented as follows:

$$h_L = \frac{C_f L}{C^{1.85} D^{4.87}} Q^{1.85} \quad \text{(Equation 2-3)}$$

where

h_L = head loss due to friction, in ft (m)

C_f = Unit conversion factor (4.73 in British units; 10.7 in Metric units)

D = pipe diameter, in ft (m)

L = length of pipe, in ft (m)

Q = pipe flow rate, in ft^3/sec (m^3/sec)

C = Hazen-Williams coefficient (dimensionless)

2.1.3 Basic Hydraulic Model Input Characterization

Building a network model, particularly if a large number of pipes are involved, is a complex process. The following categories of information are needed to construct a hydraulic model:

- Characteristics of the pipe network components (pipes, pumps, tanks, valves).
- Water use (demands) assigned to nodes (temporal variations required in EPS).
- Topographic information (elevations assigned to nodes).
- Control information that describes how the system is operated (e.g., mode of pump operation).
- Solution parameters (e.g., time steps, tolerances as required by the solution techniques).

Commonly used methods for these inputs are briefly described in the following subsections.

2.1.3.1 Pipe Network Inputs

Construction of the pipe network and its characteristics may be done manually or through use of existing spatial databases stored in GIS or CAD packages. Most commonly, GIS or CAD packages are used in this process and are described in more detail in Chapter 6. The initial step in constructing a network model is to identify pipes to be included in the model. Nodes are usually placed at pipe junctions, or at major facilities (tanks, pumps, control valves), or where pipe characteristics change in diameter, "C"-value (roughness), or material of construction. Nodes may also be placed at locations of known pressure or at sampling locations or at locations where water is used (demand nodes). The required pipe network component information includes the following:

- pipes (length, diameter, roughness factor),
- pumps (pump curve),
- valves (settings), and
- tanks (cross section information, minimum and maximum water levels).

2.1.3.2 Water Demand Inputs

Water consumption or water demand is the driving force behind the operation of a water distribution system. Any location at which water leaves the system can be characterized as a demand on the system. The water demands are aggregated and assigned to nodes, which represents an obvious simplification of real-world situations in which individual house taps are distributed along a pipe rather than at junction nodes. It is important to be able to determine the amount of water being used, where it is being used, and how this usage varies with time (Walski et al., 2003). Demand may be estimated by a count of structures of different types using a representative consumption per structure, meter readings and the assignment of each meter to a node, and to general land use. A universal adjustment factor should be used to account for losses and other unaccounted water usage so that total usage in the

Early software packages limited the number of pipes that could be included due to computer storage restrictions. This led to the concept of "skeletonizing" a network or including only those pipes that were considered to be the most important. The degree of skeletonization that is acceptable should depend upon the ultimate use of the model. For example, master plans and energy studies might be based on the use of skeletonized networks. Other applications, such as water quality modeling and designing flushing programs, require a model that includes more pipes. Though there is no national standard for skeletonization, the EPA draft guidance issued for modeling to support the IDSE under DBPR2 suggests inclusion of (EPA, 2003):

- At least 50 percent of total pipe length in the distribution system.
- At least 75 percent of the pipe volume in the distribution system.
- All 12-inch diameter and larger pipes.
- All 8-inch and larger pipes that connect pressure zones, influence zones from different sources, storage facilities, major demand areas, pumps, and control valves, or are known or expected to be significant conveyors of water.
- All 6-inch and larger pipes that connect remote areas of a distribution system to the main portion of the system.
- All storage facilities with controls or settings applied to govern the open/closed status of the facility that reflect standard operations.
- All active pump stations with realistic controls or settings applied to govern their on/off status that reflect standard operations.
- All active control valves or other system features that could significantly affect the flow of water through the distribution system (e.g., interconnections with other systems, valving between pressure zones).

A case study presented in Section 7.3.1 illustrates the use of models in support of IDSE.

Most modern software packages support an unlimited number of pipes; however, skeletonization is still frequently used in order to reduce the modeling effort. A minimal skeletonization should include all pipes and features of major concern.

model corresponds to total production.

In order to use a model in the EPS mode, information on temporal variations in water usage over the period being modeled are required. Spatially different temporal patterns can be applied to the individual network nodes. The best available information should be used for developing temporal patterns in order to make EPS most effective. For example, some users may have continuous water metering data, while others may use literature values as a first approximation for estimating residential temporal patterns. Temporal patterns also vary with climate. For example, lawn watering in summer months will cause a spike in usage of water during that time period. In some cases, information from SCADA systems can be used to estimate system-wide temporal patterns.

A typical hierarchy for assigning demands includes the following:

- Baseline Demands: Baseline demands usually correspond to consumer demands and unaccounted-for-water associated with average day conditions. This information is often acquired from a water utility's existing records, such as customer meter and billing records. Although the spatial assignment of these demands is extremely important and should include the assignment of customer classes such as industrial, residential, and commercial use, actual metering data should be used when available.
- Seasonal Variation: Water use typically varies over the course of the year with higher demands occurring in warmer months. When developing a steady-state model, the baseline (average day) demand can be modified by multipliers in order to reflect other conditions such as maximum day demand, peak-hour demand, and minimum day demand.
- Fire Demands: Water provided for fire services can be the most important consideration in developing design standards for water systems. Typically, a system is modeled corresponding to maximum-use conditions, with needed fire-flow added to a single node at a time. It is not uncommon for a requirement that multiple hydrants be flowing simultaneously.
- Diurnal Variation: All water systems are unsteady due to continuously varying demands. It is important to account for these variations in order to achieve an adequate hydraulic model. Diurnal varying demand curves should be developed for each major consumer class or geographic zones within a service area. For example, diurnal demand curves might be developed for industrial establishments, commercial establishments, and residences. Large users such as manufacturing facilities may have unique usage patterns.

Future water use: For design and planning purposes, a water system must be examined under future conditions. In situations where a system is largely currently built out, future demands may be estimated by developing global or regional multipliers that are applied to current demands. However, in new or developing areas, existing water use does not provide a useful basis for estimating future demands. Alternative approaches use population-based projections, socioeconomic modeling, and land-use methods (Johnson and Loux, 2004).

In estimating future demands for use in a network model, the most appropriate method is generally the land-use method. The land-use method is based on mapping land uses and then applying a water-use factor to each land-use category. When applied to existing situations or in historical reconstruction of water systems, aerial photographs are most commonly used as the base map for identifying land-use categories. For development of future demands, land–use maps can be obtained from planners. The land-use methodology is depicted in Figure 2-2.

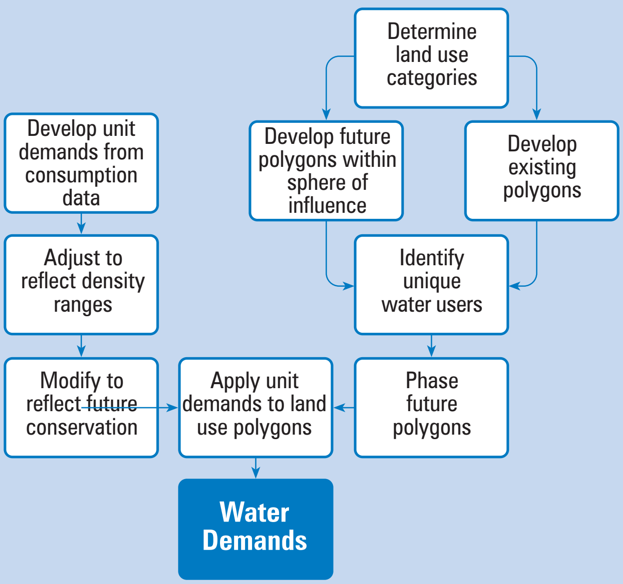


Figure 2-2. A Flow Chart for Estimating Future Water Demand Based on Land-Use Methodology.

Land-use unit demands or water-use factors are typically developed in units of gallons per day (GPD) per acre from local historical consumption data or from available regional information. GIS technology is frequently used as a means of developing and manipulating the land-use polygons and assigning the calculated demands to the model nodes.

2.1.3.3 Topographical Inputs

Hydraulic models use elevation data to convert heads to pressure. Actual pipe elevations should be used to establish the correct hydraulic gradeline. Elevations are assigned to each node in a network where pressure information is required. Various techniques are used to determine elevation information including the following:

- Topographical maps: Paper topographical maps produced by the United States Geological Survey (USGS) or other local agencies may be used to manually interpolate elevations for nodes. The relative accuracy depends upon the degree of topography in the area, the contour elevations on the map, and the manual takeoff methods used.
- Digital elevation models (DEM): USGS and other agencies produce digital files containing topographical information. When used with various software tools, elevation information can be directly interpolated and assigned to nodes based on the coordinates of the nodes. The accuracy of this process depends upon the degree of detail in the DEM.
- Global Positioning Systems (GPS) or other field survey methods: Standard field surveying techniques or modern surveying methods using a GPS satellite can be used to measure elevations at nodes. The modern GPS units can calculate elevation by using four or more satellites. However, elevation is the most difficult calculation for a GPS unit, and depending upon the location surveyed, it may be prone to significant error.

2.1.3.4 Model Control Inputs

In order to apply an EPS model, it is necessary to define a set of rules that tells the model how the water system operates. This may be as simple as specifying that a particular pump operates from 7:00 AM to 10:00 AM each day. Alternatively, it may be a set of complex "logical controls" in which operations such as pump off/on, pump speed, or valve status are controlled using Boolean operators (including if-then-else logic) for factors such as tank water levels, node pressures, system demand, and time of day (Grayman and Rossman, 1994). For water systems that operate automatically based on a set of rules, determination of these rules are quite straightforward. For manual systems, the rules must be determined by interviews with system operators.

2.1.3.5 Extended Period Simulation (EPS) Solution Parameters

Solution techniques used to iteratively solve the set of non-linear equations typically have various global parameters that control the solution technique. These parameters may be time-step lengths for EPS runs or tolerance factors that tell the model when a solution is considered to have converged. The user must specify the values for the solution parameters, or (as is frequently done) accept the default values that are built into the software products. The specific solution parameters vary between solution techniques and specific software products.

2.1.4 General Criteria for Model Selection and Application

The initial step in modeling is to define the basic scope and needs of the modeling process and to select an appropriate software package that will satisfy both the specific needs of the current project and likely future needs. Factors that may enter into the selection of a software package include:

- technical features,
- training/support and manuals,
- user interface,
- integration with other software (such as GIS, CAD),
- compatibility with EPANET,
- cost, and
- response from existing users.

A summary of major available hydraulic-water quality modeling software is provided in Section 2.3.2. Once a suitable model has been selected, the following steps should be followed in applying network models (Clark and Grayman, 1998):

- Develop the basic network model.
- Calibrate and validate the model.
- Establish clear objectives and apply the model in a manner to meet the objectives.
- Analyze and display the results.

2.1.4.1 Developing a Basic Network Model

The basic network model inputs should be first characterized using the techniques described in Section 2.1.3. The model should be developed based on accurate, up-to-date information. Information should be entered carefully and checked frequently. Following the entry of the data, an initial run of the model should be made to check for reasonableness.

2.1.4.2 Model Calibration and Validation

Calibration is an integral aspect of the art of modeling water distribution systems. Model calibration is the process of adjusting model input data (or, in some cases, model structure) so that the simulated hydraulic and water quality output sufficiently mirrors observed field data. Depending on the degree of accuracy desired, calibration can be difficult, costly, and time-consuming. The extent and difficulty of calibration are minimized by developing an accurate set of basic inputs that provide a good representation of the real network and its components.

A traditional technique for calibration is the use of "fire-flow" tests. In a fire-flow test, the system is stressed by opening hydrants to increase flows in small parts of the system. This results in increased headloss in pipes in the vicinity of the test. Pressures and flow are then measured in the field. Model parameters, such as roughness factors (C), demands, and valve positions, are adjusted so that the model adequately reflects the field data. Another common calibration technique is to measure predicted tank/reservoir levels derived from computer simulations against actual tank levels during a given period of record. For example, using water level, pressure, or flow data from SCADA systems or from on-line pressure and tank-level recorders, model parameters (such as roughness, water demands, and pump controls) can be adjusted in the simulation model until the model results match the actual tank level and other continuous information for the defined criteria. The resulting optimal parameter values should be checked to ensure that the values are realistic. Sophisticated commercial hydraulic models, such as those listed in Section 2.4, may also incorporate optimization components that aid the user in selecting system parameters resulting in the best match between observed system performance and model results (Walski, 2003).

Model validation is the step that follows calibration and uses an independent field data set to verify that the model is well calibrated. In the validation step, the calibrated model is run under conditions differing from those used for calibration and the results compared to field data. If the model results closely approximate the field results (visually) for an appropriate time period, the calibrated model is considered to be validated. Significant deviations indicate that further calibration is required. A variety of calibration and validation techniques suitable to both large and small water utilities are discussed in Chapter 4 of this document.

> Another rigorous methodology for calibration and validation is the use of tracers. Concentrations of naturally occurring materials or added chemical tracers may be measured in the field and the results used to calibrate hydraulic and water quality models. This methodology is further described in Chapter 3 of this document.

2.1.4.3 Establishing Objectives and Model Application

Prior to applying the model, the specific modeling objectives should be clearly established. The objectives may include specification of particular water demand and operational modes. Based on these specifications, a series of scenarios can be defined and the model applied appropriately. Some software products contain a scenario manager that helps the user to define and manage a large number of specific model runs. Additional scenarios can be developed in order to test the sensitivity of the system to variations in model parameters that are not known with certainty.

2.1.4.4 Analysis and Display of Results

Water distribution system models generate a large amount of output. The amount of calculated information increases with increasing model size and, for EPS, the duration of the model run. Modern water distribution system analysis software typically provides a range of graphical and tabular displays that help the user wade through the large amount of output data so that it may be efficiently analyzed. Figures 2-3, 2-4, and 2-5 contain examples of various graphical and tabular outputs generated by the EPANET software. These outputs represent a small subset of types of graphics generated by most modeling software. The output should be analyzed to ensure that the model is operating properly and to extract the information required in order to analyze the specific problem being studied.

2.2 Modeling Water Quality In Distribution System Networks

Water quality models use the output of hydraulic models in conjunction with additional inputs (described later in this section) to predict the temporal and spatial distribution of a variety of constituents within a distribution system. These constituents include:

- The fraction of water originating from a particular source.
- The age of water (e.g., duration since leaving the source).
- The concentration of a non-reactive constituent or tracer compound either added to or removed from the system (e.g., chloride or fluoride).
- The concentration of a reactive compound including the concentration of a secondary disinfectant with additional input of its loss rate (e.g., chlorine or chloramines) and the concentration of disinfection by-products with their growth rate (e.g., THMs).

The following subsection provides a brief history of water quality modeling, an overview of theoretical concepts related to water quality modeling, basic model inputs, and model application.

2.2.1 History of Water Quality Modeling

The use of models to determine the spatial pattern of

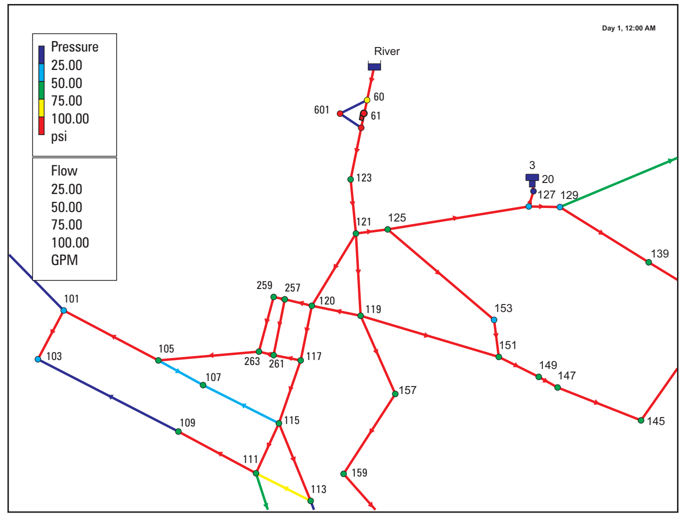


Figure 2-3. EPANET Graphical Output Showing Flow and Pressure.

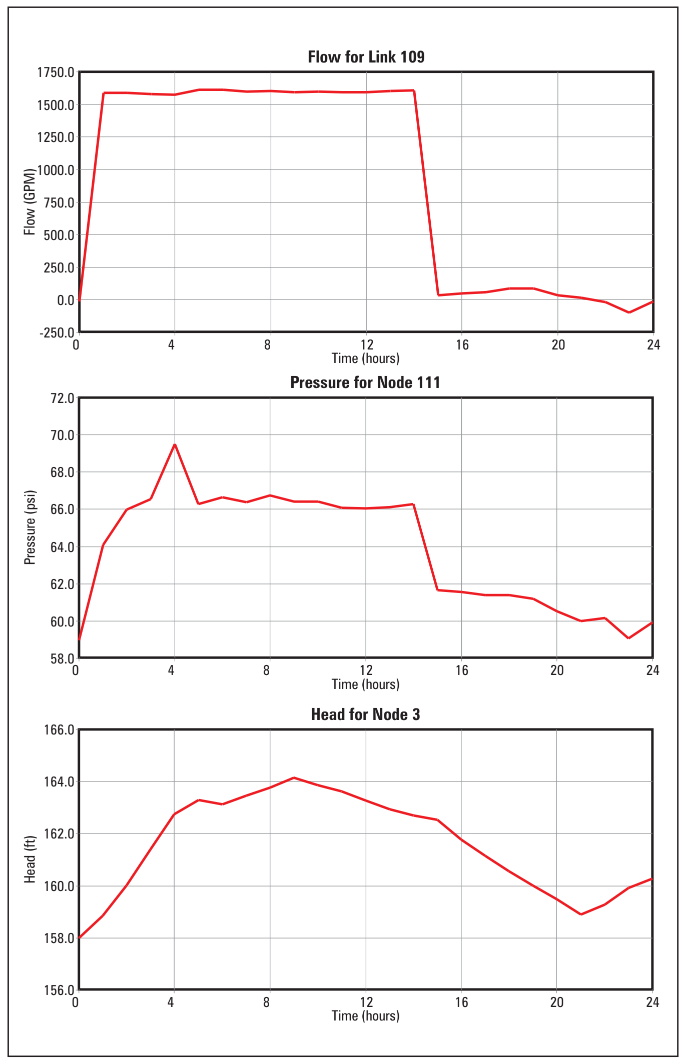
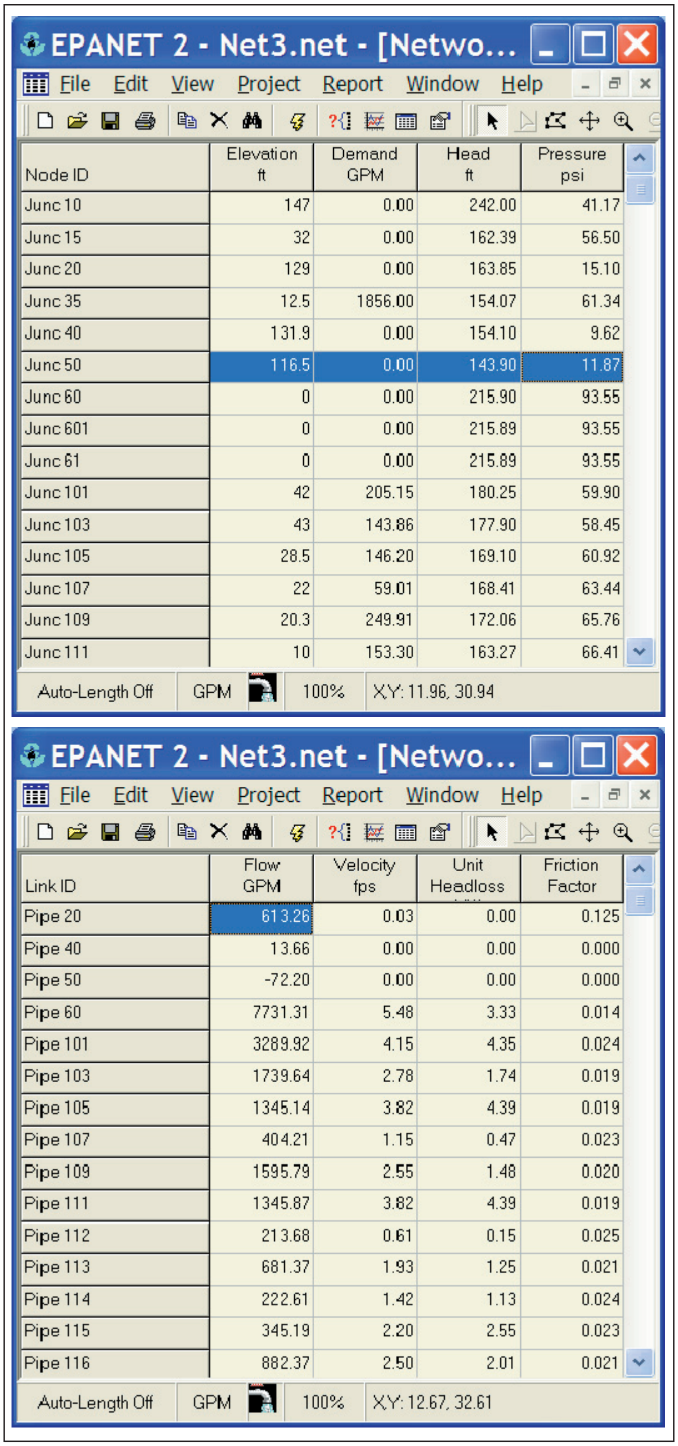


Figure 2-4. Sample EPANET Time Series Plots of Flow, Pressure, and Tank Water Level.



EPANET 2 - Net3.net - [Netwo...

Node ID	Elevation ft	Demand GPM	Head ft	Pressure psi
Junc 10	147	0.00	242.00	41.17
Junc 15	32	0.00	162.39	56.50
Junc 20	129	0.00	163.85	15.10
Junc 35	12.5	1856.00	154.07	61.34
Junc 40	131.9	0.00	154.10	9.62
Junc 50	116.5	0.00	143.90	11.87
Junc 60	0	0.00	215.90	93.55
Junc 601	0	0.00	215.89	93.55
Junc 61	0	0.00	215.89	93.55
Junc 101	42	205.15	180.25	59.90
Junc 103	43	143.86	177.90	58.45
Junc 105	28.5	146.20	169.10	60.92
Junc 107	22	59.01	168.41	63.44
Junc 109	20.3	249.91	172.06	65.76
Junc 111	10	153.30	163.27	66.41

Auto-Length Off | GPM | 100% | XY: 11.96, 30.94

EPANET 2 - Net3.net - [Netwo...

Link ID	Flow GPM	Velocity fps	Unit Headloss	Friction Factor
Pipe 20	613.26	0.03	0.00	0.125
Pipe 40	13.66	0.00	0.00	0.000
Pipe 50	-72.20	0.00	0.00	0.000
Pipe 60	7731.31	5.48	3.33	0.014
Pipe 101	3289.92	4.15	4.35	0.024
Pipe 103	1739.64	2.78	1.74	0.019
Pipe 105	1345.14	3.82	4.39	0.019
Pipe 107	404.21	1.15	0.47	0.023
Pipe 109	1595.79	2.55	1.48	0.020
Pipe 111	1345.87	3.82	4.39	0.019
Pipe 112	213.68	0.61	0.15	0.025
Pipe 113	681.37	1.93	1.25	0.021
Pipe 114	222.61	1.42	1.13	0.024
Pipe 115	345.19	2.20	2.55	0.023
Pipe 116	882.37	2.50	2.01	0.021

Auto-Length Off | GPM | 100% | XY: 12.67, 32.61

Figure 2-5. EPANET Sample Tabular Outputs (at time 10.00 hrs).

The ability to model the transport and fate of the water constituents in a distribution system can help utility managers perform a variety of water quality studies. Examples include:

- Locating and sizing storage tanks and modifying system operation to reduce water age.
- Modifying system design and operation to provide a desired blend of waters from different sources.
- Finding the best combination of: i) pipe replacement, relining, and cleaning; ii) reduction in storage holding time; iii) location and injection rate of booster stations to maintain desired disinfectant levels throughout the system.
- Assessing and minimizing the risk of consumer exposure to disinfectant by-products.
- Assessing system vulnerability to incidents of external contamination.
- Designing a cost-efficient, routine monitoring program to identify water quality variations and potential problems.

water quality in a distribution system resulting from sources of differing quality was suggested by Wood (1980b) in a study of slurry flow in a pipe network. The steady-state hydraulic model was extended by solving a series of simultaneous equations at each node. In a generalization of this formulation, Males et al., (1985) used simultaneous equations to calculate the spatial distribution of variables that could be associated with links and nodes such as concentration, travel times, costs, and others. This model, called SOLVER, was a component of the Water Supply Simulation Model (WSSM), an integrated data base management, modeling, and display system that was used to model water quality in networks (Clark and Males, 1986). A more general "marching out" solution was proposed by Males et al., (1988). Although steady-state water quality models provided some general understanding of water quality behavior in distribution systems, the need for models that would represent contaminant dynamics was recognized. This resulted in the introduction of three such dynamic models in the mid-1980s (Clark et al., 1986; Liou and Kroon, 1986; and Hart et al., 1986).

The history and proliferation of water quality modeling in distribution systems can be traced back to two expert workshops that were convened in 1991 and in 2003. The results of these workshops are presented in AWWARF/USEPA (1991) and Powell et al., (2004). Figure 2-6 illustrates the evolution of hydraulic and water quality models since the 1930s.

2.2.2 Theoretical Concepts for Water Quality Modeling

Various water quality processes are occurring in water distribution systems that can lead to introduction of contaminants and water quality transformations (see Figure 1-2, presented earlier in Chapter 1) as water moves through the distribution system. Cross connections, failures at the treatment barrier, and

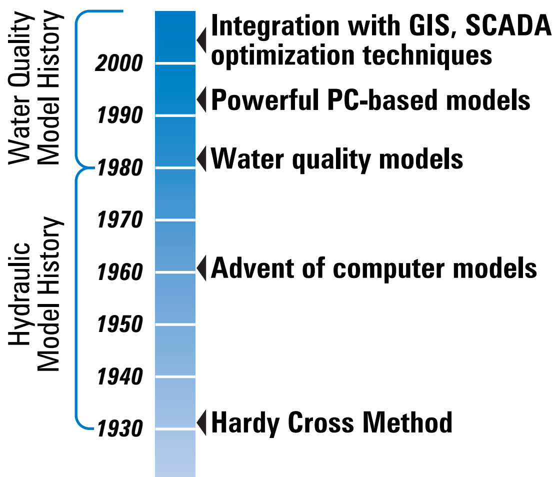


Figure 2-6. Illustration of the Evolution of Hydraulic and Water Quality Models.

transformations in the bulk phase can all degrade water quality. Corrosion, leaching of pipe material, biofilm formation, and scour can occur at the pipe wall to degrade water quality. Bacteriological quality changes may cause aesthetic problems involving taste and odor development, discolored water, and other adverse impacts.

In addition to the basic hydraulic modeling equations presented earlier in this chapter, the water quality models utilize various mathematical equations that are based on conservation of constituent mass. These models represent the following phenomena occurring in a distribution system (Rossman et al., 2000):

- Advective transport of mass within pipes: A dissolved substance will travel down the length of a pipe with the same average velocity as the carrier fluid while at the same time reacting (either growing or decaying) at some given rate. Longitudinal dispersion is not an important transport mechanism in turbulent flow, which is normal inside transmission mains under most operating conditions. It may, however, be an important factor in dead-end pipes or in low and intermittent flow scenarios.
- Mixing of mass at pipe junctions: All water quality models assume that, at junctions receiving inflow from two or more pipes, the mixing of fluid is complete and instantaneous. Thus, the concentration of a substance in water leaving the junction is simply the flow-weighted sum of the concentrations in the inflowing pipes.
- Mixing of mass within storage tanks: Most water quality models assume that the contents of storage tanks are completely mixed. See the discussion in Section 2.4.1 for further details and alternative representations.
- Reactions within pipes and storage tanks: While a substance moves down a pipe or resides in storage, it can undergo reaction. The rate of reaction, measured in mass reacted per volume of water per unit of time, will depend on the type of water quality constituent being modeled. Some constituents, such as fluoride, do not react and are termed "conservative." Other constituents, such as chlorine residual, decay with time; while the generation of DBPs, such as THMs, may increase over time. Some constituents, such as chlorine, will react with materials both in the bulk liquid phase and at the liquid-pipe wall boundary.

Water quality models represent these phenomena (transport within pipes, mixing at junctions and storage tanks, and reaction kinetics in the bulk liquid phase and at the liquid-pipe wall boundary) with a set of mathematical equations. These equations are then solved under an appropriate set of boundary and initial conditions to predict the variation of water quality throughout the distribution system.

Several solution methods are available for dynamic water quality models (Rossman and Boulos, 1996). All of these methods require that a hydraulic analysis be run first to determine how flow quantities and directions change from one time period to another throughout the pipe network. The water quality constituent is subsequently routed through each pipe link and then mixed at downstream nodes with other inflows into the node. For non-conservative substances, concentrations are continuously adjusted to accommodate the decay or growth of the constituent with time. This concentration is then released from the node into its out-flowing pipes. This process continues for all pipes and for the duration of the simulation.

The methods described above are also applied when modeling water age and source-tracing in water quality models. Water age is equivalent to modeling a reactive constituent that ages and combines linearly. For example, for every hour that a "packet" of water spends in a tank, its age will increase by one hour. Additionally, combining a volume of water that is four days old with a similar volume of water that is eight days old will result in an average age of six days. When modeling the fraction of water coming from a designated source (source tracing), this parameter is modeled as a conservative substance and is linearly combined. For example, combining a volume of water that is entirely from the designated source with a similar volume of water from a different

Modeling the movement of a contaminant within the distribution systems as it moves through the system from various points of entry (e.g., wells or treatment plants) to water users is based on three principles:

- Conservation of mass within differential lengths of pipe.
- Complete and instantaneous mixing of the water entering pipe junctions.
- Appropriate kinetic expressions for the growth or decay of the substance as it flows through pipes and storage facilities.

This change in concentration can be expressed by the following differential equation:

$$\frac{dC_{ij}}{dt} = -v_{ij}\frac{\partial C_{ij}}{\partial x} + k_{ij}C_{ij} \qquad \text{(Equation 2-5)}$$

where

C_{ij} = substance concentration (mg/L) at position x and time t in the link between nodes i and j.

v_{ij} = flow velocity in the link (equal to the link's flow rate divided by its cross-sectional area) (m/sec)

k_{ij} = rate at which the substance reacts within the link (sec^{-1})

According to Equation 2-5, the rate at which the mass of material changes within a small section of pipe equals the difference in mass flow into and out of the section plus the rate of reaction within the section. It is assumed that the velocities in the links are known beforehand from the solution to a hydraulic model of the network. In order to solve Equation 2-5, one needs to know C_{ij} at x=0 for all times (a boundary condition) and a value for k_{ij}.

Equation 2-6 represents the concentration of material leaving the junction and entering a pipe:

$$C_{ij@x=0} = \frac{\sum_k Q_{ki} C_{kj@x=L}}{\sum_k Q_{kj}} \qquad \text{(Equation 2-6)}$$

where

$C_{ij@x=0}$ = the concentration at the start of the link connecting node i to node j in mg/L (i.e.,where x=0)

$C_{kj@x=L}$ = the concentration at the end of a link, in mg/L

Q_{kj} = flow from k to i

Equation 2-6 states that the concentration leaving a junction equals the total mass of a substance flowing into the junction divided by the total flow into the junction.

source will provide a mixed volume calculated as 50 percent from the designated source.

2.2.3 Water Quality Model Inputs and Application

In addition to the basic hydraulic model inputs described in Section 2.1.3, the water quality models require the following data elements to simulate the behavior in a distribution system:

- Water Quality Boundary Conditions - A water quality model requires the quality of all external inflows to the network and the water quality throughout the network be specified at the start of the simulation. Data on external inflows can be obtained from existing source monitoring records when simulating existing operations or could be set to desired values to investigate operational changes. Initial water quality values can be estimated based on field data. Alternatively, best estimates can be made for initial conditions. Then the model is run for a sufficiently long period of time under a repeating pattern of source and demand inputs so that the initial conditions, especially in storage tanks, do not influence the water quality predictions in the distribution system. The water age and source tracing options only require input from the hydraulic model.

- Reaction Rate Data – For non-conservative substances, information is needed on how the constituents decay or grow over time. Modeling the fate of a residual disinfectant is one of the most common applications of network water quality models. The two most frequently used disinfectants in distribution systems are chlorine and chloramines (a reactant of chlorine and ammonia). Free chlorine is more reactive than chloramine and its reaction kinetics have been studied more extensively. Studies have shown that there are two separate reaction mechanisms for chlorine decay, one involving reactions within the bulk fluid and another involving reactions with material on or released from the pipe wall (Vasconcelos et al., 1997). Bulk decay is typically represented as a first order exponential decay function with a single decay coefficient specified to represent the decay over time. In some circumstances, this function does not adequately represent the observed decay characteristics, and more complex formulations may be used to describe the decay. Wall reaction represents the disinfectant decay due to contact with oxidizeable substances at the pipe wall, such as corrosion products or biofilm. The most widely used approach for representing wall demand considers two interacting processes – transport

Storage tanks are usually modeled as completely mixed, variable volume reactors in which the changes in volume and concentration over time are as follows:

$$\frac{dV_s}{dt} = \sum_k Q_{ks} - \sum_i Q_{sj} \quad \text{(Equation 2-7)}$$

$$\frac{dV_s C_s}{dt} = \sum_k Q_{ks} C_{ks@x=L} - \sum_i Q_{sj} C_s + k_{ij}(C_s) \quad \text{(Equation 2-8)}$$

where

C_s = the concentration for tanks, in mg/L

dt = change in time, in seconds

Q_{ks} = flow from node k to s, in ft^3/sec (m^3/sec)

Q_{sj} = flow from node s to j, in ft^3/sec (m^3/sec)

dV_s = change in volume of tank at nodes, in ft^3(m^3)

V = volume of tank at nodes, in ft^3(m^3)

C_{ks} = concentration of contaminant in link ks, in mg/ft^3 (mg/m^3)

k_{il} = decay coeficient between nodes i and j, in sec^{-1}

Many algorithms and methods exist for the numerical solution of fluid flows described by the Navier-Stokes equations. These algorithms can be classified as Eulerian or Lagrangian and as either time-driven or event-driven. In a Eulerian method, the movement of the fluid is viewed from a stationary grid as the water moves through the system. On the contrary, in a Lagrangian method, the analysis is viewed from a framework that is moving with the flow. Time-driven methods assess the system at fixed time steps. Event-driven methods evaluate the system only when there is a discrete change in water quality such as a pulse of water with different concentrations entering or leaving a pipe. Various methodologies combine either Eulerian or Lagrangian solutions (or hybrid combinations of these two cases) with either time-driven or event-driven procedures.

of the disinfectant from the bulk flow to the wall and interaction with the wall (Rossman et al., 1994). Recent studies have suggested that this formulation may not adequately represent the actual wall demand processes and that further research is needed (Clark et al., 2005; Grayman et al., 2002; DiGiano and Zhang, 2004). There has been little study on the nature of the wall reaction in chloraminated systems. A limited amount of modeling of the growth of DBPs (most notably THMs) has been performed assuming an exponential growth approaching a maximum value corresponding to the THM formation potential. Both the formation potential and the growth rate constant must be specified in this type of model (Clark et al., 1996). There has been extensive research on biofilm formation in distribution systems and this has led to the development of several theoretical models of this phenomenon (Powell et al., 2004). However, these models are generally quite complex involving many parameters that are difficult to determine, and thus are not ready for inclusion in a general water distribution system model.

The following section provides an overview of available software for hydraulic and water quality modeling.

Distribution system water quality models are generally limited to tracking the dynamics of a single component (e.g., chlorine, water age) at a time when the selected component is transported throughout the network of pipes and storage tanks. Such models do not consider interactions between different components in the flowing water or complex reactions between components that are transported with the water and surface components that are fixed to the pipe wall. This can be a significant limitation when modeling reactive components, for example when chlorine residual is modeled for a case where there are multiple sources with significant differences in water quality characteristics. Another more complex example that is not adequately represented by the single-species model is modeling of DBP formation. A solution to this deficiency is a general-purpose, multi-species capability that is being added to EPANET (Uber et al., 2004). This addition will allow users to program their own chemical/physical/biological reactions in EPANET with almost unlimited interaction capability between multiple species.

2.3 Hydraulic and Water Quality Modeling Software

A variety of software packages are available to perform hydraulic and water quality modeling. A majority of these packages utilize the EPANET formulation as the basic computation engine. A full discussion of individual software packages is beyond the scope of this document. The following subsections briefly describe the EPANET model and summarize the features of other available software.

2.3.1 EPANET Software

EPANET was initially developed in 1993 as a distribution system hydraulic-water quality model to support research efforts at EPA (Rossman et al., 1994). The development of the EPANET software has also satisfied the need for a comprehensive public-sector model and has served as the hydraulic and water quality "engine" for many commercial models.

EPANET can be used for both steady-state and EPS hydraulic simulations. In addition, it is designed to be a research tool for modeling the movement and fate of drinking water constituents within distribution systems. EPANET can be operated in the SI (metric) or British systems of measurement.

The water quality routines in EPANET can be used to model concentrations of reactive and conservative substances, changes in age of water and travel time to a node, and the percentage of water reaching any node from any other node. Outputs from EPANET include:

- color-coded network maps,
- time series plots, and
- tabular reports.

Example outputs from EPANET were previously presented in Figures 2-3, 2-4, and 2-5.

2.3.2 Commercial Hydraulic-Water Quality Modeling Software

In addition to EPANET, there are several commercial software packages that are widely used in the U.S. and internationally. Most of these packages are based on the EPANET formulation and include value-added components as parts of GUI that increase the capability of the software. Examples of such value-added components that are part of one or more of the commercially available software packages include:

- Scenario manager: Manage inputs and outputs of a group of model runs.
- Calibration optimization: Utilize genetic algorithm optimization technique to determine model parameters that best fit a set of field data.
- Design optimization: Utilize genetic algorithm optimization techniques to select pipe sizes that minimize costs or other selected objectives.
- Integration with GIS or CAD: Water distribution model directly integrates with GIS or CAD to assist in constructing or updating model and display results.
- Flexible output graphics: Provides convenient ways to modify parameters for graphical displays of output data.
- Energy management: Calculates energy use for a selected alternative.
- Automated fire-flow analysis: Assesses the availability of fire flow at a range of nodes and determines whether a system meets fire-flow requirements.
- Water security and vulnerability assessment methods, skeletonization, and demand allocation tools.

Table 2-1 provides a summary listing of major commercial software and a Web link where additional details may be obtained on specific features and current version availability/pricing.

> In addition to the standard use of EPANET in a Windows environment using the graphical user interface (GUI), the functionality of EPANET can be accessed through the EPANET toolkit. The toolkit is a series of open source routines available in both Visual Basic and C (programming language) that can be used as is or modified and accessed from a user's own computer program. This powerful capability has been widely used throughout the world to support both research and specific applications in the field of water distribution system analysis.

2.4 Additional Modeling Tools

In addition to standard hydraulic and water quality modeling of distribution systems, there are several other related types of models that can be used to assess hydraulic and water quality behavior in distribution systems. These include: storage modeling tools, transient (water hammer) modeling tools, optimization tools, and probabilistic models. Each of these types of models are briefly described and demonstrated in the following sections.

2.4.1 Storage Modeling Tools

An important aspect of water quality and contaminant propagation in drinking water distribution systems is the effect of system storage. Most utilities use some type of ground or elevated storage system to process water during time periods when treatment facilities would otherwise be idle. It is then possible to distribute and store water at one or more locations in the service area closest to the user.

The principal advantage of distribution storage is that it equalizes demands on supply sources, production works, and transmission and distribution mains. As a result, the sizes or capacities of these elements may be minimized and peak power tariff periods for pumping can often be avoided. Additionally, system flows and pressures are improved and stabilized to better serve the customers throughout the service area. Finally, reserve supplies are provided in the distribution system for emergencies, such as fire fighting and power outages.

In most municipal water systems, less than 25 percent of the volume of the storage in tanks is actively used (on a daily basis) under routine conditions. As the

Table 2-1. Available Hydraulic and Water Quality Network Modeling Software Packages

Network Modeling Software	Company	EPANET Based	Website
AQUIS	Seven Technologies		www.7t.dk/aquis
EPANET	EPA	X	www.epa.gov/ord/nrmrl/wswrd/epanet.html
InfoWater H2ONET/H2OMAP	MWHSoft	X	www.mwhsoft.com
InfoWorks WS	Wallingford Software		www.wallingfordsoftware.com
MikeNet	DHI, Boss International	X	www.dhisoftware.com/mikenet
Pipe2000	University of Kentucky		www.kypipe.com
PipelineNet	SAIC, TSWG	X	www.tswg.gov/tswg/ip/pipelinenettb.htm
SynerGEE Water	Advantica		www.advantica.biz
WaterCAD/WaterGEMS	Haestad Methods	X	www.haestad.com
STANET	Fisher-Uhrig Engineering		www.stanet.net
Wadiso	GLS Eng. Software	X	www.wadiso.com

water level drops, tank controls require high-service pumps to start in order to satisfy demand and refilling of the tanks. The remaining water in the tanks (70 to 75 percent) is normally held in reserve as dedicated fire or emergency storage. This water tends to be stagnant and may cause water quality problems.

Storage tanks and reservoirs are the most visible components of a water distribution system, but are often the least understood in terms of their effect on water quality. Although these facilities can play a major role in providing hydraulic reliability for fire fighting needs and in providing reliable service, they may also serve as vessels for unwanted complex chemical and biological changes that may result in the deterioration of water quality. These storage tanks and reservoirs also contribute to increased residence time in drinking water systems. This increased residence time can contribute to the loss of disinfectant residuals and cause subsequent growth of microorganisms. Modeling can provide information on what will happen in existing, modified or proposed distribution system tanks and reservoirs under a range of operating situations (Grayman et al., 2004a).

Three primary types of models are used for representing storage tanks and reservoirs: computational fluid dynamics (CFD) models, compartment models, and physical scale models. In mathematical models, equations are written to simulate the behavior of water in a tank or reservoir. These models range from detailed representations of the hydraulic mixing phenomena in the facility called CFD models to simplified conceptual representations of the mixing behavior called compartment or systems models. Physical scale models are constructed from materials such as wood or plastic. Dyes or chemicals are used to trace the movement of water through the model.

2.4.1.1 CFD Models

CFD models use mathematical equations to simulate flow patterns, heat transfer, and chemical reactions. Partial differential equations representing conservation of mass, momentum, and energy are solved numerically for a two- or three-dimensional grid that approximates the geometry of the tank. CFD modeling has been used widely in the chemical, nuclear, and mechanical engineering fields, and in recent years has emerged as a modeling tool in the drinking water industry (Grayman and Arnold, 2003). CFD models can be used to simulate temperature variations, unsteady hydraulic and water quality conditions, and decay of constituents in storage facilities. Significant experience is required to apply CFD models, and model run times of many hours, days, or even weeks are required for complex situations. Figure 2-7 depicts a graphical output from a CFD model showing the concentration throughout a tank at a snapshot in time resulting from a tracer that has been injected into the inflow.

Many generalized CFD software packages are available that can be used to construct CFD models of tanks. Examples of such packages are listed in Table 2-2. These packages vary in terms of capabilities, solution methods, ease of use, and support. Prior to selection of a package, the specific needs and capabilities of the user should be carefully evaluated.

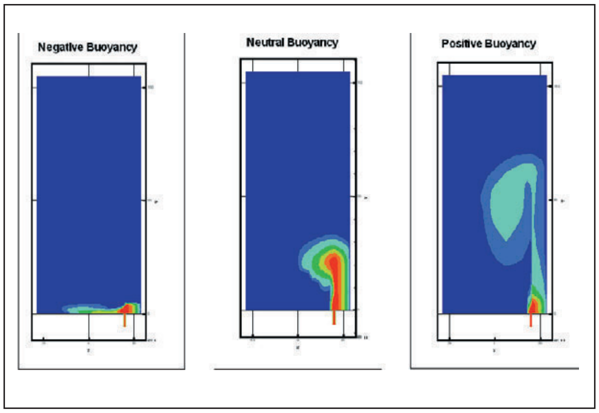


Figure 2-7. Graphical Output from a CFD Model Showing Tracer Concentration in a Tank.

Generally the purchase or lease of these packages is significant (typically on the order of $25,000 per year) and significant training/expertise is required to effectively apply them.

2.4.1.2 Compartment Models

Compartment models are a class of models in which physical processes (i.e., the mixing phenomena in the tank or reservoir) are represented by highly conceptual, empirical relationships. This type of model is also referred to as a black box model, or input-output model. Since such models do not use detailed mathematical equations to describe the movement of water within the tank, they rely on engineering judgment or upon field data and past experience to define the parameters that control the behavior of the model. Compartment models are used in water distribution network models to represent mixing in tanks and reservoirs. Various assumptions can be made in these models about the mixing behavior in tanks including complete and instantaneous mixing, plug flow, last-in/first-out (LIFO) behavior, and multi-compartment models. Both conservative substances and substances that decay according to a first-order decay function may be simulated in addition to simulation of water age. Compartment models are relatively easy to use and run in seconds as opposed to the long run times of CFD models.

Compartment models of tanks are available as part of most water distribution system models. EPANET and several of its derivative commercial models allow the user to select from four options – a complete mix model, a plug flow first-in/first-out (FIFO) model, a LIFO (short circuiting) model and a two-compartment model. A stand-alone model called CompTank provides a wide range of alternatives and allows the user to model water age and reactive or conservative substances over a long period of time (Grayman et al., 2000). This model uses tank inflow and outflow information that is generally available from SCADA records as its primary input.

Table 2-2. Example CFD Modeling Software Packages

CFD Package	Company	Website
CFD-ACE	CFD Research Corp.	www.cfdrc.com
Cfdesign	Blue Ridge Numerics	www.brni.com
CFX	Ansys, Inc.	www.software.aeat.com/cfx
FLOW-3D	Flow Science, Inc.	www.flow3d.com
Fluent	Fluent, Inc.	www.fluent.com
Phoenics	CHAM	www.cham.co.uk
SWIFT	AVL	www.avl.com
Sinda/Fluint	C&R Technologies	www.crtech.com
PAB3D	Analytical Services & Materials	www.asm-usa.com

2.4.1.3 Physical Scale Models

Physical scale models provide a relatively inexpensive mechanism for studying the mixing characteristics of tanks. In a physical scale model, a tracer chemical is added to the inflow (or internally within the model) and the movement of the tracer is monitored during the experiment (Grayman et al., 2000). Tracer substances include visible dyes, which are appropriate for developing a qualitative understanding of mixing behavior, and chemicals (e.g., calcium chloride) that can be measured by sensors in the tanks and used for quantitative assessments. Use of tracers of different density or careful control of temperature of the tracer can be used to study the impacts of thermal variations on mixing. Laws of similitude in hydraulics must be followed in order to account for the scaling effects. Scale models can vary in size and complexity from small tabletop models to large-scale models built in hydraulics laboratories. Figure 2-8 depicts such a large-scale model.

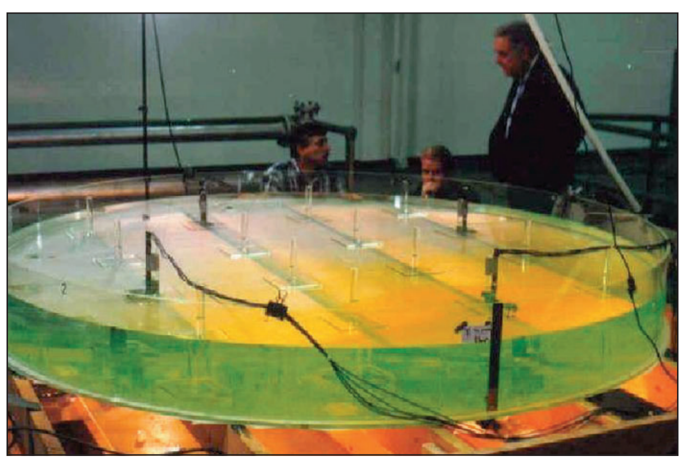


Figure 2-8. A Large Physical Model of a Tank (Source: Bureau of Reclamation Laboratory).

In an advanced technology form of physical scale modeling, three-dimensional laser induced fluorescence is being used to provide detailed measurements of mixing in tanks (Roberts and Tian, 2002). Figure 2-9 shows an illustration of output from this technology.

2.4.2 Transient Analysis Software

A hydraulic transient is a rapid change in pressure associated with a pressure wave that moves rapidly through a piping system. A transient can be caused by a variety of events, such as rapid operation of a valve (including fire hydrants) or rapid pump starts and stops. If the magnitude of the resulting pressure wave is large enough and adequate transient control measures are not in place, a transient can cause a water hammer leading to failure of hydraulic components. It can also lead to instantaneous low or negative pressures that can result in intrusion of untreated water into the pipe, potentially resulting in contamination. Transient events are highly dynamic and sophisticated. Mathematical models are required to analyze their movement in a distribution system.

Several commercial software packages for performing transient analysis in water distribution systems are available. Examples of such software are listed in Table 2-3. The technical capabilities, user interface, solution methods, graphical display, and technical support and training vary considerably among the packages.

2.4.3 Optimization Tools

Optimization tools allow the user to evaluate a large number of options and to select the specific alternative that gives the best results in terms of predefined objective functions. In the area of water distribution system analysis, optimization models are used for calibration, design, and operational purposes. These applications are briefly described in the following subsections.

2.4.3.1 Optimizing Calibration

Calibration of a water distribution system model involves adjustments in various model parameters so that the model agrees with field measurements of flow and pressure. Such a tool is used most frequently with flow and pressure measurements taken during flow (hydrant) tests to stress the system. Parameters that are typically adjusted include roughness factors, demands, and status of isolation valves.

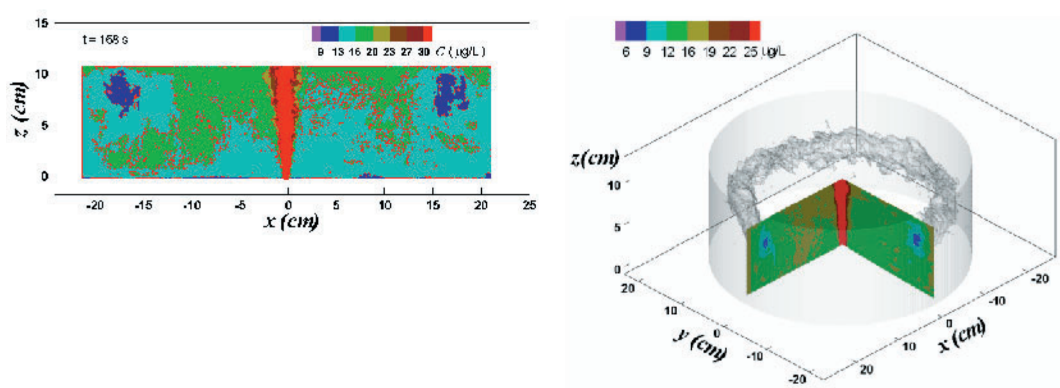


Figure 2-9. Graphical Output Based on 3-D Laser Induced Fluorescence with a Physical Scale Model Showing Mixing in Tank (Source: Georgia Tech).

Table 2-3. Example Transient Modeling Software Packages

Transient Modeling Software	Company	Website
AQUIS Surge	Seven Technologies	www.7t.dk/aquis
HAMMER	Haestad Methods	www.haestad.com
Hytran v3.0	Hytran Solutions	www.hytran.net
Impulse	Applied Flow Technology	www.aft.com/products/impulse
InfoSurge, H2OSurge	MWHSoft	www.mwhsoft.com

The production of transient low-and negative-pressures in otherwise pressurized drinking water supply distribution systems creates the opportunity for contaminated water to enter the pipe from outside. Such events may be caused by the sudden shutdown of pumps or by other operational events such as flushing, hydrant use, and main breaks. Figure 2-10 illustrates an event that results in a negative pressure transient for 22 seconds caused by a power outage associated with a lightning strike.

In a series of research projects (LeChevallier et al., 2003; Gullick et al., 2004), the frequency and location of low-and negative-pressures in representative distribution systems were measured under normal operating conditions and during specific operational events. These investigators also confirmed that fecal indicators and culturable human viruses were present in the soil and water exterior to the distribution system pipes. Their research shows that a well-calibrated hydraulic surge model can be used to simulate the occurrence of pressure transients under a variety of operational scenarios, and a model can also be used to determine optimal mitigation measures.

Although there are insufficient data to indicate whether pressure transients pose a substantial risk to water quality in the distribution system, mitigation techniques can be implemented. These techniques include the maintenance of an effective disinfectant residual throughout the distribution system, leak control, redesign of air relief venting, installation of hydro-pneumatic tanks, and more rigorous application of existing engineering standards.

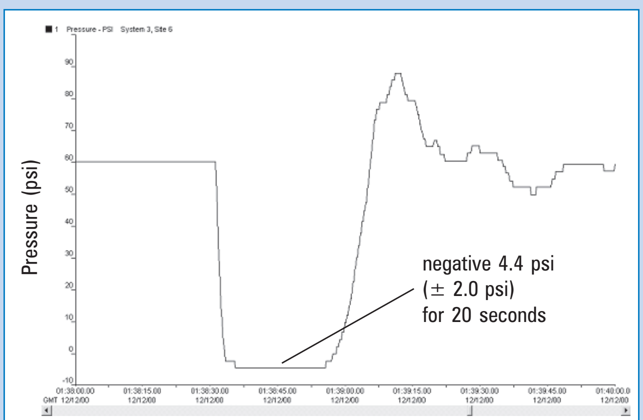


Figure 2-10. Negative Pressure Transient Associated with a Power Outage.

Use of manual adjustment techniques may involve many tedious runs of a distribution system model until the resulting predicted flows and pressures approximate the values observed in the field. When an optimization model is applied, the user defines an objective function, such as minimizing the square of the difference between observed and predicted values (for pressure and flow). The optimization algorithm then uses some type of controlled search method to identify the set of model parameters that will result in the best results (i.e., minimize the error). The user will generally set constraints on parameters so that the resulting values are reasonable. For example, the user may specify that the allowable range for the roughness factor for a certain set of ductile iron pipes range between 90 and 120.

Over the past 40 years, various techniques have been applied as part of automated calibration methods (Rahal et al., 1980; Walski et al., 2003). The most common optimization technique in use today couples a hydraulic model with an optimization routine using genetic algorithms. Genetic algorithms are based on the theory of genetics in which successive population trials are generated with the "fittest" ones surviving to breed and evolve into increasingly desirable offspring solutions. The fitness of a solution is based on the objective functions that were previously described. Genetic algorithm-based calibration tools are available as optional components of several water distribution system analysis software packages.

2.4.3.2 Design Optimization

In a manner analogous to the calibration optimization technique described above, design optimization techniques evaluate a large number of distribution system design options and select the one that provides the best solution (Lansey, 2000). Schaake and Lai (1969) first proposed such an approach and applied it to the design of major transmission lines providing water to New York City. Since that time, numerous papers have been written on the subject (Walski et al., 2003) and have included a variety of techniques such as linear programming, dynamic programming, mixed integer programming, heuristic algorithms, gradient search methods, enumeration methods, genetic algorithms, and simulated annealing. In recent years, genetic algorithm methods have been favored for this problem and have been widely used in a variety of situations and are included in several commercial software packages. The user should, however, be aware that genetic algorithms do not guarantee optimality. These algorithms must be run several times to ensure near optimal solutions.

Typically, design optimization tools limit a user to choose from designated piping options and to size the pipes to meet present and future demands. Cost minimization is the most common objective function.

Additionally, some researchers have incorporated reliability and capacity considerations (Mays, 1989).

2.4.3.3 Optimization of Operation

Models can also be used to optimize operations of a distribution system (Goldman et al., 2000). The most common areas of operation where such models have been applied are in energy management and water quality. Chase et al. (1994) describe a computer program to control energy costs that incorporates a hydraulic model, a pump optimization program, and an interface. In the water quality area, Uber et al. (2003) used optimization techniques to determine optimal location and operation of chlorine booster stations. Jentgen et al. (2003) implemented a prototype energy and water quality management system at Colorado Springs Utilities. This system combines a simplified distribution system model and an optimization routine to adjust operation of the water system and power generation system in near real-time.

2.4.4 Probabilistic Models

Hydraulic and water quality models of distribution systems are deterministic models. For a set of network parameters and specific operations and demands, the model produces a single set of resulting flows and pressures. However, there is uncertainty in many of the aspects of these models including parameters such as roughness, demands, actual inside diameter of pipes, valve settings, and system controls. This uncertainty is generally due to both imperfect knowledge and natural variability. An emerging procedure is to embed a deterministic network model within a probabilistic framework and to examine the effect of uncertainty on the results.

The most common approach to incorporating uncertainty in models is the use of a Monte Carlo simulation (Vose, 2000). In this method, probability distributions are assigned to model parameters to represent the uncertainty associated with each parameter. The distribution system model is then run many times with parameter values being randomly drawn from the probability distributions. The results of many iterations are combined to determine the most likely result and a distribution of results. This approach has been used in legal cases where historical contamination events have been reconstructed (Grayman et al., 2004b), in evaluation of the impacts of purposeful contamination (Murray et al., 2004) and modeling bacterial regrowth in distribution systems (DiGiano and Zhang, 2004).

2.5 Summary and Conclusions

Acquiring and utilizing the proper data is very important for implementing water distribution system models. The key inputs include the characterization of the pipe network (e.g., pipes, pumps, tanks, and valves), water-demand information (temporal variations are required in EPS), topographic information (elevations assigned to nodes), control information that describes how the system is operated, and EPS solution parameters (e.g., time steps, tolerances as required by the solution techniques). Periodic calibration and validation of a model is important to achieve optimum results.

Models have become widely accepted within the water utility industry as a mechanism to simulate the hydraulic and water quality behavior of a real or proposed distribution system. They are routinely used for a number of tasks including capital investment decisions, master plan development, and fire protection capacity design. Furthermore, these models have become very sophisticated and typically simulate both hydraulic and water quality behavior. Many modeling packages are integrated with GIS or CAD. Some software packages incorporate water hammers and tank mixing. EPANET is a public sector hydraulic/water quality model developed by EPA. EPANET also serves as the computation engine for many of the commercial models used by water utilities throughout the country. In addition to EPANET and EPANET-based water distribution system models, there are several other tools available to users for studying specific needs, such as transient analysis and optimization analysis.

To successfully apply a model to study a problem, one should clearly define the objectives and select an appropriate tool. Thereafter, understanding the accuracy of the input data and limitations of the model will enable the user to better interpret the results of the analysis and develop appropriate solutions.

Many of the assumptions and methodologies in use today in water distribution system modeling date back to the early work of Hardy Cross (1936). With the monumental increase in computational power and improvements in the ability to measure flow in experimental distribution systems, it is natural that some of the basic assumptions are being examined and challenged. Three notable examples of active research areas include the following:

- Distribution system water quality models currently assume advective flow that results in water quality pulses moving through a pipe without spreading out longitudinally. Lee and Buchberger (2001) have studied pipe flow and found that dispersion has a significant effect on concentration profiles, especially in cases of intermittent laminar flow. Lee (2004) developed an analytical equation which describes the unsteady dispersion of changing flow velocity in pipes based on the classic one-dimensional advection-dispersion equation by Taylor (1953). Tzatchkov et al., (2002) have developed an extension to the standard EPANET model that includes dispersion.

- In distribution system models, deterministic demands are assigned to nodes. Buchberger et al., (2003) monitored water use at the individual home and neighborhood level and found that there are significant short-term variations in water use. They have developed a model that represents water use as a series of pulses which can be simulated using a Poisson Rectangular Pulse model to capture the natural variability associated with water use.

- Distribution system models currently assume complete mixing at a junction. As a result, if there are two pipes with flow entering the junction and two pipes through which the flow exits, the chemical content of the water in the two exiting pipes will be identical and represent an average of the characteristics of the two entering pipes. Van Bloemen Waanders et al., (2005) have tested this assumption using both laboratory analysis and CFD modeling. Figure 2-11a depicts the velocity field at a junction. Figure 2-11b presents the corresponding tracer concentrations at that junction. The figures indicate that the complete mix assumption would lead to some inaccuracy in computing chemical transport in a distribution system.

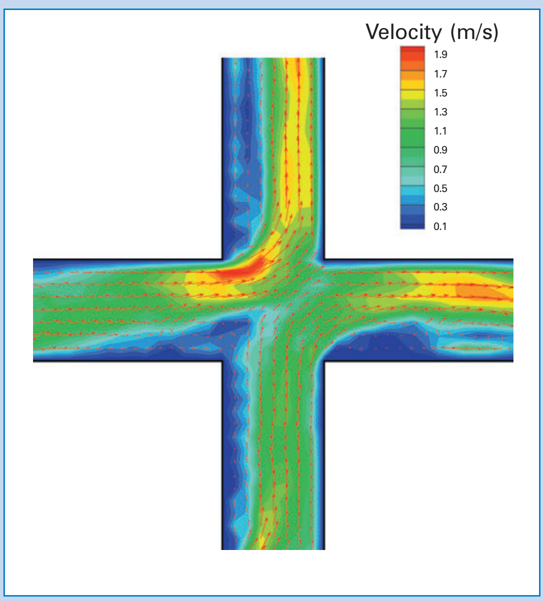


Figure 2-11a. Velocity Field at a Junction.

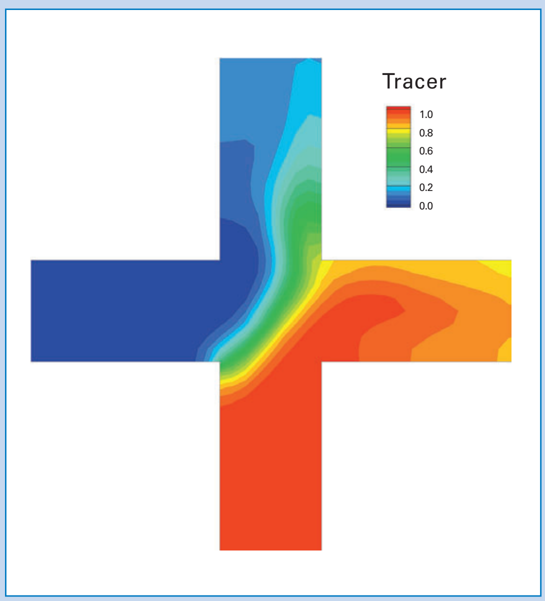


Figure 2-11b. Tracer Concentration at a Junction.

References

American Water Works Association (AWWA). *Computer Modeling of Water Distribution Systems, AWWA Manual M-32*, Denver, CO. 2004.

AwwaRF/U.S. EPA. *Water Quality Modeling in Distribution Systems.* Edited by W.M. Grayman, R.M. Clark, and R.M. Males. AwwaRF-AWWA. Denver. CO. 1991.

Buchberger, S.G., J.T. Carter, Y.H. Lee, and T.G. Schade. "Random Demands, Travel Times, and Water Quality in Deadends." AwwaRF/AWWA, Denver, CO. 2003.

Bureau of Reclamation Laboratory. Photo provided by Bates Engineering, Inc., 2004.

Chase, D.V., D. Guastella, K.L Lai, and L.E. Ormsbee. "Energy Management for Large Scale Water Supply Systems." AWWA Computer Conference, Los Angeles, CA. 1994.

Clark, R.M., W.M. Grayman, R.M. Males, and J.A. Coyle. "Predicting Water Quality in Distribution Systems." Proceedings, AWWA Distribution System Symposium, Minneapolis, MN. 1986.

Clark, R.M., and R.M. Males. "Developing and Applying the Water Supply Simulation Model," *Journal of AWWA*, 78(8). 1986.

Clark, R.M., and W.M. Grayman. *Modeling Water Quality in Drinking Water Systems.* AWWA. 1998.

Clark R.M., R.C. Haught, and W.M. Grayman. "Predicting Chlorine Residuals in Unlined Metallic Pipes." Proceedings, ASCE-EWRI World Water & Environmental Resources Congress, Anchorage, AK. 2005.

Clark, R.M., H. Pourmaghaddas, L.G. Wymer, and R.C. Dressman. "Modeling the Kinetics of Chlorination By-Product Formation: The Effects of Bromide," *Journal Water Supply Research and Technology - Aqua*, 45(1):1-8. 1996.

Cross, H. "Analysis of Flow in Networks of Conduits or Conductors," *University of Illinois Engineering Experiment Station Bulletin 286*, Urbana, IL. 1936.

DiGiano, F. A., and W. Zhang. "Uncertainty Analysis in a Mechanistic Model of Bacterial Regrowth in Distribution System." *Environmental Science and Technology* 38:22:5925-5931. 2004.

EPA. *Stage 2 Disinfectants and Disinfection Byproducts Initial Distribution System Evaluation Guidance Manual, Draft*. 2003.

Georgia Tech. Photo provided by Dr. Philip J. W. Roberts, School of Civil Engineering, Georgia Institute of Technology, 2004.

Goldman, F.E., A.B.A. Sakarya, L.E. Ormsbee, J.G. Uber, and L.W. Mays. "Optimization Models for Operation." Chapter in *Water Distribution System Handbook*. Edited by Larry Mays for McGraw-Hill, NY. 2000.

Grayman, W.M., R.M. Clark, and R.M. Males. "Modeling Distribution System Water Quality Dynamic Approach," *Journal of Water Resources Planning and Management*, ASCE, 114(3). 1988.

Grayman, W.M. "Put Your Hydraulic Model to Work – How That Costly Model Can Earn its Keep by Making Operations More Effective." Proceedings, AWWA Annual Conference, Denver, CO. 2000.

Grayman, W.M., L.A. Rossman, M.A. Gill, Y. Li, and D.E. Guastella. "Measuring and Modeling Disinfectant Wall Demand in Metallic Pipes." Proceedings, EWRI Conference on Water Resources Planning and Management, Reston VA. ASCE. 2002.

Grayman, W.M., L.A. Rossman, R.A. Deininger, C.D. Smith., C.N. Arnold., and J.F. Smith. "Mixing and Aging of Water in Distribution System Storage Facilities." *Journal of AWWA*, 96(9):70-80. 2004a.

Grayman W.M., R.M. Clark, B.L. Harding, M. Maslia, and J. Aramini. "Reconstructing Historical Contamination Events," Chapter in *Water Supply Systems Security*. Edited by Larry Mays, McGraw-Hill, NY. 2004b.

Grayman, W.M., and C. N. Arnold. "Overview of CFD Methods in Analysis of Distribution System Tanks and Reservoirs." Proceedings, AWWA Annual Conference, AWWA, Denver, CO. 2003.

Grayman, W.M., and L.A. Rossman. "Integrating a Network Model with an Expert System." Proceedings, AWWA Computer Conference, AWWA, Denver, CO. 1994.

Grayman, W.M., L.A. Rossman, C.N. Arnold, R.A. Deininger, C.D. Smith, J.F. Smith, and R. Schnipke. *Water Quality Modeling of Distribution System Storage Facilities.* AwwaRF and AWWA. 2000.

Gullick, R.W., M.W. LeChevallier, R.C. Svindland, and M. Friedman. "Occurrence of Transient Low and Negative Pressures in Distribution Systems." *Journal of AWWA*. 96(11): 52-66. November 2004.

Hart, F.L., J.L. Meader, and S.N. Chiang. "CLNET A Simulation Model for Tracing Chlorine Residuals in a Potable Water Distribution Network." Proceedings, AWWA Distribution System Symposium, Minneapolis, MN. 1986.

Jentgen, L., S. Conrad, R. Riddle, E. Von Sacken, K. Stone, W.M. Grayman, and S. Ranade. *Implementing a Prototype Energy and Water Quality Management System.* AwwaRF, Denver, CO. 2003.

Jeppson, R.W. *Analysis of Flow in Pipe Networks.* Ann Arbor Science, Ann Arbor, MI. 1976.

Johnson K.E., and J. Loux. *Water and Land Use: Planning Wisely For California's Future.* Solano Press, Point Arena, CA. 2004.

Lansey, K.E. "Optimal Design of Water Distribution Systems." Chapter in *Water Distribution System Handbook.* Edited by Larry Mays for McGraw-Hill, NY. 2000.

Larock, B.E., R.W. Jeppson, and G.Z. Watters. *Hydraulics of Pipeline Systems.* CRC Press, LLC, Boca Raton, FL. pp 12-26. 2000.

LeChevallier, M.W., R.W. Gullick, M.R. Karim, M. Friedman and J.E. Funk. "The Potential for Health Risks from Intrusion of Contaminants into the Distribution System from Pressure Transients," *Journal of Water and Health,* IWA Publishing. pp. 3-14. January 2003.

Lee, Y. and S.G. Buchberger. "Estimation of dispersion in unsteady random flow conditions in dead-end pipes of water distribution systems." Proceedings, ASCE-EWRI World Water & Environmental Resources Congress, Orlando, FL. 2001.

Lee, Y. Mass Dispersion in Intermittent Laminar Flow. Ph.D. Dissertation in Civil and Environmental Engineering, University of Cincinnati, Cincinnati, Ohio. 2004.

Liou, C.P., and J.R. Kroon. "Propagation and Distribution of Waterborne Substances in Networks," Proceedings, AWWA Distribution System Symposium, Minneapolis, MN. 1986.

Males, R.M., R.M. Clark, P.J. Wehrman, and W.E. Gates. "Algorithm for Mixing Problems in Water Systems," *Journal Hydraulic Engineering*, ASCE, 111(2). 1985.

Males, R.M., W.M. Grayman, R.M. Clark. "Modeling Water Quality in Distribution Systems," *Journal Water Resources Planning and Management*, ASCE, 114(2). 1988.

Mays, L.W., Editor. *Reliability Analysis of Water Distribution Systems.* ASCE. NY. 1989.

Murray, R., R. Janke, and J. Uber. "The Threat Ensemble Vulnerability Assessment (TEVA) Program for Drinking Water Distribution System Security." Proceedings, ASCE-EWRI World Water & Environmental Resources Congress, Salt Lake City, UT. 2004.

Powell, J., J. Clement, M. Brandt, R. Casey, D. Holt, W. Grayman, and M. LeChevallier. "Predictive Models for Water Quality in Distribution Systems." AwwaRF, Denver, CO. 2004.

Rahal, C.M., M.J.H. Sterling, and B. Coulbeck. "Parameter Tuning for Simulation Methods of Water Distribution Networks." Proceedings, Institute of Civil Engineers, Part 269, 751. 1980.

Roberts, P.J.W., and X. Tian. "Application of Three-Dimensional Laser-Induced Fluorescence to Stratified Turbulent Mixing Processes." Proceedings, ASCE Hydraulic Measurements and Experiments Conference. 2002.

Rossman, L.A., and P.F. Boulos. "Numerical Methods for Modeling Water Quality in Distribution Systems: A Comparison." *Journal Water Resources Planning and Management*, ASCE, 122(2):137-146. 1996.

Rossman, L.A. *EPANET Version 2 Users Manual*, Drinking Water Research Division, EPA, Cincinnati, OH. 2000.

Rossman, L.A., R.M. Clark, and W.M. Grayman. "Modeling Chlorine Residuals in Drinking Water Distribution Systems." *Journal Environmental Engineering,* 120(4):803-820. 1994.

Schaake, J., and D. Lai. *Linear Programming and Dynamic Programming Applications to Water Distribution Network Design - Report 116.* Department of Civil Engineering, MIT, Cambridge, MA. 1969.

Taylor, G.I. "Dispersion of soluble matter in solvent flowing slowly through a tube," *Journal of the Royal Society of London Series A*, The Royal Society, London, UK. 219:186-203. 1953.

Tzatchkov, V.G., A.A. Aldama, and F.I. Arreguin. "Advection-dispersion Reaction Modeling in Water Distribution Networks." *Journal Water Resources Planning & Management*, 128(5):334-342. 2002.

Uber, J., F. Shang, M. Polycarpou, and Z.Wang. "Feedback Control of Booster Chlorination Systems." AwwaRF, Denver, CO. 2003.

Uber, J., F. Shang, and L. Rossman. "Extensions to EPANET for Fate and Transport of Multiple Interacting Chemical or Biological Components." Proceedings, ASCE-EWRI World Water & Environmental Resources Congress, Salt Lake City, UT. 2004.

Van Bloemen Waanders, B., G. Hammond, J. Shadid, S. Collis, and R. Murray. "A Comparison of Navier-Stokes and Network Models to Predict Chemical Transport in Municipal Water Distribution Systems." Proceedings, ASCE-EWRI World Water & Environmental Resources Congress, Anchorage, AK. 2005.

Vasconcelos, J.J., L.A. Rossman, W.M. Grayman, P.F. Boulos, and R.M. Clark. "Kinetics of Chlorine Decay," *Journal of AWWA*, 89(7):54-65. 1997.

Vose, D. *Risk Analysis – A Quantitative Guide.* John Wiley & Sons. Chichester, UK. 2000.

Walski, T.M., D.V. Chase, D.A. Savic, W. Grayman, S. Beckwith, and E. Koelle. *Advanced Water Distribution Modeling and Management*. Haestad Press, Waterbury, CT. 2003.

Wood, D.J. *Computer Analysis of Flow in Pipe Networks.* Department of Civil Engineering, University of Kentucky, Lexington, KY. 1980a.

Wood, D.J. "Slurry Flow in Pipe Networks." *Journal of Hydraulics*, ASCE, 106(1). May 1980b.

Chapter 3
Tracer Studies for Distribution System Evaluation

Tracers have been used for decades to determine flow, travel time, and dispersion in surface waters and groundwater. Tracers can be of various types, ranging from a physical object that can be visually detected in a stream or river to dyes or other chemicals whose concentrations can be monitored using special instrumentation. Fluorescent dyes have been used for many years to measure velocity and tidal movement in streams and estuaries. Use of tracers to understand the hydraulic movement in drinking water treatment unit processes or distribution systems is a more recent development. When tracers are used in drinking water, care must be taken to ensure that they will have no adverse health effects and that their use does not result in any violations of primary and/or secondary drinking water MCLs.

Tracers have been used in drinking water to estimate the travel time through various water treatment unit processes including clearwells (Teefy and Singer, 1990; Teefy, 1996; DiGiano et al., 2005). Tracer studies have also been conducted in distribution system tanks and reservoirs in an attempt to understand their mixing characteristics (Grayman et al., 1996; Boulos et al., 1996). They have also been used in water distribution networks to provide insight into the complex movement of water in a distribution system, to determine travel times, and to assist in calibration of distribution system hydraulic models (Clark et al., 1993; DeGiano et al., 2005; Vasconcelos et al., 1997; Grayman, 2001). For example, Boccelli et al. (2004) and Sautner et al. (2005) have used dual tracers injected into water distribution systems to assess travel time and characterize flow patterns in support of epidemiological investigations. With the recent interest in homeland security issues, tracers are being used to simulate the movement and impacts of accidental or intentional contamination of water distribution systems (Panguluri et al., 2005).

Conducting a distribution system tracer study involves (1) injecting the tracer into a pipe upstream of the area to be studied, (2) shutting off or reducing a continuous chemical feed at the water treatment plant, or (3) use of a naturally occurring substance in source water. The concentration is measured over time at various locations in the water distribution network as it moves through the study area. To be successful, a tracer study requires careful planning and implementation. This chapter provides information and guidance on planning and conducting tracer studies in drinking water distribution systems.

Tracer studies in distribution systems may provide a wide variety of useful information, including the following:

- Calculating travel time, residence time, or water age in a network.
- Calibrating a hydraulic model.
- Defining zones in a network served by a particular source and/or assessing the degree of blending with water from other sources.
- Determining the impacts of accidental or intentional contamination.
- Identifying appropriate sampling locations within the water distribution network.

Tracer studies may also assist water utilities in complying with various regulatory requirements. For example, the DBPR2 IDSE draft Guidance Manual (EPA, 2003a) recognizes the use of tracers as a means of calibrating models and predicting residence time as a partial substitute for required field monitoring. Several rules and regulations (both existing and proposed) are currently being reviewed, such as the TCR and a proposed distribution system rule. Water quality modeling and model calibration are likely to play a role in the development and/or promulgation of these rules.

The scope of a tracer study may vary considerably depending upon the study needs, size, and complexity of the distribution network being evaluated. A study area may consist of a single stretch of pipe, an entire neighborhood, a portion of a large distribution system, a pressure zone, or in some cases, the entire distribution network. The resources required to conduct a tracer study will vary with the extent, complexity of the study, and the test equipment used. Careful planning and implementation are critical in all cases to ensure meaningful results. Section 3.1 of this chapter contains information that can be used during the planning phases of a tracer study. Section 3.2 provides a summary of the tasks associated with executing a tracer study. Section 3.3 presents typical costs associated with conducting a tracer study. Finally, Section 3.4 presents a summary, conclusions, and recommendations for this chapter. The use of tracer study data for model calibration/validation is described in Chapter 4.

3.1 Planning and Designing a Distribution System Tracer Study

The initial step in any tracer study is a planning and design phase during which study-specific logistical details are identified and addressed. These details should be presented in a comprehensive manner in a planning document or work plan that can be reviewed and commented on by parties that may have an interest in the tracer study (e.g., team members, water utility staff and managers, and state regulatory officials). Planning and design-phase elements may include the following:

- Establishing study objectives and timeline.
- Forming a study team.
- Defining study area characteristics.
- Selecting tracer material.
- Selecting field equipment and procedures.
- Developing a detailed study design.
- Addressing agency and public notification.

The details of each of these tasks are described in the following sub-sections.

3.1.1 Establishing Study Objectives and Time-Line

A clear statement of the study objectives should be developed, even before logistical planning begins. For example, an objective statement might read "determine travel times from the Lincoln Water Treatment Plant to key locations (transmission mains and representative local mains) in the Washington Pressure Zone under typical summer operation." Such a statement provides a clear understanding of the study's overall goals and objectives. A study objective may also be more specific and define additional key elements such as tracer material, dosage, and injection duration.

Depending upon the objective, an approximate timeline (schedule) for the study should be formulated. Frequently, external constraints such as weather, system operation, and availability of personnel/ equipment may influence this timeline. In other cases, the project timeline may depend upon the specific objective of the study. For example, if the maximum community exposure to a contamination event is being studied, the timeline should be consistent with the season and time during which the event is likely to occur. If the study is intended to identify locations in the system where the lowest chlorine residuals are found, the study should be conducted during a period when minimum chlorine residuals occur. However, it is not always possible to conduct a tracer study to match system conditions that coincide with the study time-frame. Therefore, a reasonable alternative is to use the tracer to calibrate a study-area-specific network model, under a given set of conditions, that can be used to simulate other critical events under different conditions.

> In mid-western U. S., October-November is the best time-frame to conduct a tracer study in a residential area. During this time, the utility has greater operational flexibility because it is not stressed by high demands, weather is conducive to outdoor activity, and cold weather pipe breaks are minimal.

3.1.2 Forming a Study Team

A "tracer study team" should be formed at the beginning of the project. Depending on the size and scope of the study, the size of the team may vary from as few as three members to a sizable group of as many as twenty members. However, the range of functions and responsibilities that must be considered are approximately the same in all types of studies. The team makeup must include members with expertise for planning and carrying out the following activities and functions: understanding study area distribution system and treatment operations; conducting preliminary modeling studies; selecting, acquiring, and installing field equipment; managing and organizing field crews; performing field sampling; conducting laboratory analysis; analyzing and reporting results; and performing communications and notifications.

Study teams may be made up of water utility personnel, consulting engineering firm personnel, contractor staff, students from universities, and in some cases, federal or state governmental agency employees. Specific responsibilities and roles should be assigned to each team member. It is recommended that the study team meet on a regular basis to ensure that the task deadlines are met and the study objectives are achievable. If the tracer study includes new or never-before used equipment, training sessions for study team members should be included as part of study timeline and activities.

3.1.3 Defining Study Area Characteristics

After the study team is formed, perhaps the first task to be undertaken is to identify the key characteristics of the study area. These characteristics include: the piping system network, pumping and storage operations, inflow and outflow through study area boundaries, temporal and spatial variations in water consumption, presence of large water users that may significantly impact water use patterns, and the

When planning a tracer study, the effects of distribution system tanks and reservoirs should be considered (Grayman at al., 2004). When a tracer enters a tank in the inflow, it mixes with the distributed water and then exits the tank at a different concentration during the subsequent draw cycles. Mixing in the tank may be rapid and complete or there may be short-circuiting or plug flow behavior that affects the concentration in the effluent. Various mathematical tools such as CFD models may be applied to estimate the mixing characteristics of a tank and the effects on tracer concentration during discharge periods (Grayman et al., 2004). Distribution system models such as EPANET allow the user to simulate mixing in tanks by several alternative conceptual and simplified models such as completely and instantaneously mixed, short circuiting, plug flow, and multiple compartment mixing. The effects of tanks can impact the needed tracer dosage rate and injection duration and the subsequent sampling frequency and duration in parts of the distribution system impacted by the tank. During the tracer study, the impacts of mixing in the tank can be determined by sampling in the inflow and outflow lines, and in some cases, internally within the tank.

geography and local features associated with the study area that could potentially constrain field activities.

A large commercial user such as a golf course in the neighborhood may impact the study events.

There are several tools and procedures that can be applied to improve the team's understanding of the target water distribution system area prior to conducting the tracer study. If a hydraulic model of the distribution system (under study) is available, it would be very helpful to use the model to simulate the tracer study under expected conditions. Examination of documents, such as master plans or operational reports, can also shed light on how the water system behaves. The study team or key members of the study team should also tour the study site with as-built pipe drawings to identify potential locations for safely installing field injection equipment, as well as flow and tracer monitoring equipment.

3.1.4 Selecting Tracer Material

Criteria that can influence the selection of a particular tracer include:

- regulatory requirements,
- analytical methods and instruments available for measuring tracer concentration,
- injection and storage requirements,
- chemical reactivity,
- chemical composition of the finished water,
- overall cost, and
- public perception.

Ideally, a tracer should be inexpensive, nonreactive with both water and distribution system materials, safe to drink when dissolved in water, easily dispersed in water, aesthetically acceptable to customers, able to meet all drinking water regulations, and inexpensively and accurately monitored in the field by manual and automated methods. There is no one tracer that will meet all of these criteria for a given study. Frequently, there are tradeoffs among the criteria listed above that must be assessed when selecting a tracer. The tracer to be used in the study should be determined early in the planning stage, and approval for its use received from the water utility and state regulatory agencies.

Tracers may fall into three broad categories: a chemical that is normally added to the water during the treatment process and that may be temporarily shut off during the study; a chemical that is added to the water by the team during the study; or a naturally occurring substance in the source water that may be adjusted in some manner to create a tracer.

The most commonly used tracers are fluoride, calcium chloride, and sodium chloride.

3.1.4.1 Fluoride

Fluoride is frequently added to water supplies because of its health benefits, but can be turned off for short periods, thereby making the non-fluoridated water a tracer in the system. When fluoridation is not practiced, fluoride can be added to the water system and used as a tracer by injection. It is especially popular with utilities that routinely add fluoride as part of the treatment process, because little effort is required to turn the fluoride off and on. When the fluoride feed is shut off, a front of low-fluoride water (or no fluoride if there is no natural background concentration) becomes the tracer. A second tracer test (or a continuation of the initial test) can be performed when the fluoride feed

Fluoride can interact with coagulants that have been added during treatment and in some circumstances can interact with pipe walls leading to non-conservative behavior. Thus, when used in systems that do not generally fluoridate, a field test should be performed to determine possible interactions with pipes.

is turned back on, thus making it possible to generate two sets of tracer data in one study.

The MCL for fluoride is 4 mg/L. However, if the secondary MCL of 2 mg/L is exceeded, customers must be notified. Background levels of fluoride can vary significantly and actually exceed the secondary MCL in some geographic areas.

In cases where a utility is not permitted to completely shut off the fluoride feed, it may be feasible to increase the fluoride feed prior to the tracer study and to reduce the fluoride feed during the test. Care should be exercised to avoid exceeding the secondary MCL. However, there must be a sufficient change in the fluoride concentration feed in order to trace the change through the system. Thus, for example, a decrease in feed concentration from 1.2 mg/L to 0.8 mg/L may not be sufficient, but a decrease in concentration from 1.5 mg/L to 0.5 mg/L may be adequate. A change in fluoride dosage may have to be pre-approved by state regulators. Depending upon the duration of the study, the state agency may choose to allow a temporary shutoff or set a specific lowest allowable-fluoride-concentration requirement.

In most treatment plants, fluoride is injected prior to a final clearwell. As a result, when the feed is shut off as a part of the tracer study, there is both a time delay and a gradual change in concentration in the clearwell discharge as the non-fluoridated and fluoridated water mix. Therefore, wherever and whenever possible, the clearwell should be operated at minimum water levels during the tracer test in order to achieve a relatively sharp front of non-fluoridated water leaving the treatment plant. It is also important to evaluate the impact of travel through finished water storage reservoirs on the concentration of tracer during the study. An alternative is to inject fluoride solution (e.g., sodium fluoride) at a point in the main transmission line downstream of the clearwell where both flow and injection rate can be simultaneously monitored and measured.

In a study conducted in the Cheshire service area of the South Central Connecticut Regional Water Authority (SCCRWA) in 1989, the fluoride feed was turned off to provide a tracer to validate a hydraulic and water quality model of their water distribution system (Clark et al., 1991). This study was among the first applications of water quality models in the world. SCCRWA normally added fluoride at a level of approximately 1 mg/L. For purposes of the model validation study, the fluoride feed was turned off for a period of 7 days and then turned back on with sampling occurring for an additional 7 days. This approach yielded, in effect, two tracer fronts. During the study, grab samples were taken every few hours at 16 hydrants, two well fields, one tank, four continuous analyzer sites, and daily at 19 "deadend" sites. Additionally, experimental units were installed at a few sheltered sites to automatically measure fluoride concentrations and to take discrete samples for later analysis. A total of 2,150 fluoride grab samples were taken during the study and analyzed in the laboratory.

Ion-selective electrodes (ISE) can be used in conjunction with data loggers to provide continuous monitoring capability. At present, however, these instruments are relatively expensive (approximately $5,000 to $10,000 each) and have only been used extensively in large-scale tracer studies (Maslia et al., 2005; Sautner et al., 2005). Generally, grab samples are taken and analysis is performed manually in the field or laboratory.

Under some circumstances, fluoride is not a fully conservative chemical. In one study (Vasconcelos et al., 1996) in a system that did not normally fluoridate, a 13-hour pulse (step input of limited duration) of fluoride was injected into the feed line of a pressure zone. Field measurements of fluoride concentrations in the zone during the study indicated a significant loss of fluoride. It was postulated that some of the fluoride was deposited on the pipe wall. In a followup study, this problem was virtually eliminated by injecting fluoride over a period of several days prior to the actual study in order to pre-condition the pipes.

3.1.4.2 Calcium Chloride

Calcium chloride ($CaCl_2$) has been used in many tracer studies throughout the U.S. It is considered to be safe and relatively easy to handle. Generally, a food grade substance is required. It can be purchased as a liquid (typically a 30 to 35% solution) or as a powder that can be mixed with water to form a solution.

If calcium chloride is chosen as a tracer, the study personnel should be aware of the secondary drinking water MCL for chloride (250 mg/L). A target that is less than the secondary MCL should be set in order to provide a safety factor. Where chloride levels are high, calcium chloride may not be an appropriate choice for a tracer.

Grayman et al., (2000) utilized calcium chloride as a tracer in two studies of mixing in distribution system tanks. In both studies, the chemical was injected into the inflow pipe of the tank during the fill cycles, and conductivity and chloride were measured at locations within the tank. Calcium chloride has recently been used in several distribution system studies (Panguluri et al., 2005; Maslia et al., 2005; and Sautner et al., 2005).

Calcium chloride can be monitored by measuring conductivity, or by measuring the calcium or chloride ion (Standard Methods, 1998). Conductivity is typically the easiest of these parameters to measure and is most amenable to inexpensive continuous monitors. However, conductivity is not a truly linear parameter (i.e., if a beaker of water of conductivity 100 mS/cm is combined with a like volume of water with a conductivity of 300 mS/cm, the conductivity of the resulting solution will not be exactly 200 mS/cm). As a result, distribution system models (that all assume linearity) can only approximately represent conductivity. Therefore, when using conductivity as the measured parameter, the options are to accept the linear approximation or convert conductivity to a true linear parameter such as chloride or calcium. If the former option is chosen, the amount of resulting error should be established in laboratory tests of waters of varying conductivity. If the latter option is chosen, the relationship between conductivity and chloride (or calcium) must be established in the laboratory. It should also be noted that most field devices are set up to measure specific conductance instead of conductivity (conductivity is temperature sensitive, whereas specific conductance is referenced to 25°C). For the purposes of this document, conductivity is assumed to represent specific conductance.

3.1.4.3 Sodium Chloride

Sodium chloride (NaCl) can be used as a tracer and has many characteristics similar to calcium chloride in that it can be traced by monitoring for conductivity or for the concentration of the chloride or sodium ion. The allowable concentration for sodium chloride is also limited by the secondary MCL for chloride and the potential health impacts of elevated sodium levels. EPA reports that taste thresholds for sodium vary significantly among individuals, ranging from 30 to 460 mg/L (EPA, 2003b).

In a recent tracer study in Hillsborough County, Florida, two separate tracer chemicals were used to study the movement of water in a large distribution system (Boccelli et al., 2004). Approximately 2,200 gallons of a saturated NaCl solution was injected into the finished water of a treatment plant as a series of four pulses ranging in duration from 1 to 3 hours over a 24-hour period. Simultaneously, the normal fluoride feed was shut off at the plant. Continuous conductivity monitors were installed at 14 locations in the distribution system to monitor for the NaCl tracer. Grab samples were taken to monitor the low fluoride front as it moved through the system and to evaluate water quality changes. The resulting extensive hydraulic and water quality database is being used to calibrate a hydraulic and water quality model of the system (Boccelli and Uber, 2005).

3.1.4.4 Other Chemicals That May be Added as Tracers

Other chemicals added as part of a tracer study include lithium chloride and chlorine. Lithium chloride is a popular tracer in the United Kingdom but is used less frequently in the U.S., partly because of the public perception of lithium as a medical pharmaceutical. There are no field techniques for measuring lithium, and it is not easily amenable to automated continuous measurement. Samples must be collected and lithium concentrations measured in the laboratory.

Chlorine is commonly used as a disinfectant in many water systems. Because chlorine is reactive, it will decay over time. Under some circumstances, however, it can be used effectively as a tracer. It is most effective in a water where chlorine is not highly reactive (low decay rate) with either the water or distribution system material, and where the concentration levels can be increased above the normal level to create a front of water with a high chlorine concentration propagating through the system. However, in no case should the chlorine or chloramine be decreased to a level that may affect the disinfection process (Ferguson and DiGiano, 2005). Again, any tracer study should first be approved by the state regulators.

3.1.4.5 Naturally or Normally Occurring Tracers

Perhaps the most difficult part of conducting a tracer study is obtaining permission to add a chemical and then injecting the tracer into the system at a concentration consistent with regulations. Much of this effort can be avoided if there is a natural tracer available. Natural tracers are generally site-specific, but many options do exist and should be explored. The most common situation is the existence of multiple sources of water with different chemical signatures or if a change is planned in the chemical signature at a single source. Examples of these situations are described below.

Some of the chemical signatures that may be used to differentiate between sources include THM concentrations, hardness, conductivity, and treatment coagulant. Sampling in the distribution system for these "tracers" will provide information on zones served by each of the sources and the extent and variation of the mixing that takes place in these zones over time. Alternatively, if one water source can be turned off for a period of time until the other source has reached chemical equilibrium throughout the system, the original source can be turned back on and used as a tracer as it propagates through the system. One of the first uses of natural tracers was in the North

Making a major change in the incoming water supply such as a change in source water or modifying treatment may provide an opportunity to conduct a tracer test. The increased use of chloramines as a secondary disinfectant, to reduce the formation of DBPs, introduces another potential tracer opportunity. When a water utility switches from chlorine to chloramines (or vice versa), the chemical signature of the water changes and can be monitored by measuring both free and total chlorine. Namely, with chloramination, total chlorine is typically much higher than free chlorine, while with free chlorination, free and total chlorine will typically be very similar. A tracer study can be conducted when a system first adopts chloramination. Alternatively, many water utilities routinely switch back from chloramination to chlorine (e.g., annually for a month) in order to kill ammonia-oxidizing bacteria and thus reduce the chances of nitrification. This provides a recurring opportunity to conduct such a tracer study.

Penn Water Authority (NPWA) located in Lansdale, PA (Clark and Coyle, 1990). A field research project was conducted by EPA and NPWA that resulted in the development of a series of models that were used to study contaminant propagation in the water distribution system. The utility used a combination of groundwater with high levels of hardness and surface water containing higher levels of THMs. This resulted in two sources of water with very different quality characteristics. By monitoring changes in water quality that occurred at selected sampling points in the utility network, it was possible to use hardness and THM concentrations as tracers to validate the model.

Another case occurred in the North Marin Water District (NMWD) in northern California (Clark et al., 1994) where natural differences in water characteristics were used to serve as a tracer for validation of a water distribution system model. In this EPA-sponsored study, the utility used two sources of water with dramatically different water quality characteristics. The first source, Stafford Lake, has a very high humic content and thus has a very high THM formation potential. The other source is the North Marin Aqueduct with a very low humic content and thus a very low THM formation potential. The model was further validated by predicting chlorine residual losses at various points in the network. In a follow-up study supported by AwwaRF (Vasconcelos et al., 1997), the investigators used sodium as a tracer to validate the model.

DiGiano and Carter (2001) and DiGiano et al. (2005) traced the flow from two separate treatment plant sources at the same time by simultaneously reducing the fluoride feed at one plant while changing the coagulant added at the other plant. Normally, ferric chloride ($FeCl_3$) was used as a coagulant at both plants. During the tracer study, the coagulant at one plant was changed to aluminum sulfate [$Al_2(SO_4)_3$]. Fluoride, sulfate, and chloride were measured throughout the distribution system.

Water utilities should carefully examine their particular system to determine if a natural tracer is available or if source-chemical signatures may be modified to be used as a tracer.

Sweetwater Authority in southern California took advantage of a normal changeover in source water quality to perform a tracer study in their distribution system (Hatcher et al., 2004). In this case, the utility semi-annually changes the primary source of their water supply from local Sweetwater Reservoir raw water to water provided by the California Aqueduct. These two sources have very different chemical characteristics; most significantly, the organic carbon content (i.e., humic and fulvic acids) of Sweetwater Lake water is much higher compared to the raw aqueduct water. The measurement of molecular organic carbon absorbance at 254 nanometers, utilizing an ultra-violet-visible (UV-VIS) spectrophotometer, is a surrogate measurement for the organic carbon content in water. UV-254 measurements were taken from grab samples at the treatment plant and at 28 sites within the distribution system over the five-day changeover period. The distribution system sites included most of the TCR sampling sites in addition to selected tanks. The resulting database was used to assess the movement of water in the system, the travel time throughout the system, boundary zones in the distribution system between areas served by the surface water plant and secondary sources, and calibration/validation of the distribution system model.

3.1.4.6 Comparison of Tracers

Teefy (1996) investigated tracer alternatives for use in studies of residence time in clearwells and described the chemical characteristics of the individual tracers. Table 3-1 summarizes various chemical characteristics identified in that report.

There are advantages and disadvantages associated with each of the general types of tracers: conservative (non reactive) tracers, reactive tracers, chemicals that are normally added to the water but can be turned off, and natural chemical signatures in the finished water. Conservative tracers are more easily modeled than non-conservative tracers. Natural tracers or chemicals that can be turned off are easier to use than injected chemicals. Certain chemicals are more amenable to continuous monitors. These and other factors should all be considered when selecting a tracer for a study.

Table 3-1. Tracer Characteristics (adapted from Teefy, 1996)

	Fluoride	Calcium	Sodium	Lithium	Chloride
Commonly available forms	H_2SiF_6 NaF Na_2SiF_6	$CaCl_2$	NaCl	dry LiCl	$CaCl_2$ NaCl KCl
Analytical methods	IC, ISE, SPADNS method	AA, IC, ICP, EDTA titration Conductivity	AA, IC, ICP, FEP Conductivity	AA, IC, ICP, FEP	IC, ISE, $AgNO_3$ titration, $Hg(NO_3)_2$ titration
Typical chemical cost	Food-grade H_2SiF_6 $7.6/100 lb - 23.97% liquid[1] $140/55 gallons - 49% liquid[2]	Food-grade $CaCl_2$ $150/55 gallons - 35% liquid[3]	Food-grade NaCl $12/50 lb[4] $6/50 lb[5]	Lab-grade LiCl[6] $22 - $48/500g[7]	Food-grade NaCl $12/50 lb[4] $6/50 lb[5]
Typical analytical cost per sample	$18[8] (IC) $16[10] (IC) $12[11] (ISE) $25[12] (IC)	$10[8] (ICP) $12[10] (ICPMS) $5[11] (ICP)	$10[8] (ICP) $12[10] (ICPMS) $5[11] (ICP)	$12[8] (ICP[9]) $12[10] (ICPMS) $6[11] (AA[13])	$18[8] (IC) $16[10] (IC) $12[10] (EPA 325.3) $12[11] (IC)
Typical background levels in water distribution systems	0-4 mg/L	Varies greatly (1-300 mg/L), use only when low	Varies greatly (1-500 mg/L)	Usually below 5 mg/L	Varies greatly (1-250 mg/L)
Regulatory limits	4 mg/L SDWA MCL, 2 mg/L secondary MCL	None known. See limits for chloride.	20 mg/L for restricted diet (EPA recommendation)	None known. See limits for chloride.	250 mg/L secondary standard

[1] Provided by Lucier Chemical Industries (LCI), Ltd., http://www.lciltd.com

[2] Provided by Bonded Chemicals, Inc., http://www.chemgroup.com/bci.htm

[3] Provided by Benbow Chemical Packaging, Inc., http://www.benbowchemical.com

[4] Provided by Skidmore Sales and Distributing Company, Inc., http://www.skidmore-sales.com

[5] Provided by Ulrich Chemical, Inc., http://www.ulrichchem.com

[6] Food grade LiCl is not available.

[7] Provided by Science Kit & Boreal Laboratories, http://www.sciencekit.com

[8] Provided by Severn Trent Laboratories (STL) North Canton, Ohio, http://www.stl-inc.com. Prices are based on a large sample volume (> 500 samples).

[9] STL North Canton Laboratory is not certified for Lithium test in Ohio.

[10] Provided by SPL Laboratories, Inc., http://www.spl-inc.com Prices are based on a large sample volume (> 500 samples).

[11] Provided by Environmental Enterprises, Inc., http://www.eeienv.com Prices are based on a large sample volume (> 500 samples).

[12] Provided by FOH Environmental Laboratory for the CDC study at Camp Lejeune, NC. http://www.foh.dhhs.gov/. The analytical cost per sample includes cost for providing a sample bottle and report.

[13] Environmental Enterprises, Inc. is not certified for Lithium test.

Note: Tracers

$CaCl_2$	calcium chloride
H_2SiF_6	hydrofluosilicic acid
KCl	potassium chloride
LiCl	lithium chloride
NaF	sodium fluoride
Na_2SiF_6	sodium silicofluoride
NaCl	sodium chloride

Analytical methods

AA	atomic absorption spectrometry
$AgNO_3$	silver nitrate
EDTA	ethylenediaminetetraacetic acid
FEP	flame emission photometric method
$Hg(NO_3)_2$	mercuric nitrate
IC	ion chromatography
ICP	inductively coupled plasma
ISE	ion selective electrode
SPADNS	Trisodium (4,5-Dihydroxy-3-[(p-sulfophenyl)-2,7-) naphthalene disulfonic acid

After investigating tracer options and selecting the most appropriate tracer, the governing state drinking water agency should be contacted. The agency should be provided with the specifics regarding the proposed study including location(s), proposed time-line(s) and selected tracer material. Once agreement has been reached and consent is received, the study team can then proceed with the next steps in the planning process.

3.1.5 Selecting Field Equipment and Procedures

Once a tracer has been selected and approval has been received from the appropriate water utility managers and regulatory agencies, specialized equipment must be identified and procured, including injection pumps, temporary tracer storage tanks, and various flow and tracer monitoring equipment (e.g., tracer chemical, reagents, and/or sample bottles). Vendors should be contacted for technical information, equipment availability, and cost quotations for the required field equipment and analytical instrumentation. The major decisions to be made and the items to be purchased prior to the execution of the study are discussed in the following subsections.

3.1.5.1 Injection Pump(s)

Pumps that are typically used in drinking water applications can be broadly classified as centrifugal pumps or positive displacement pumps. The centrifugal pumps produce a head and a flow by increasing the velocity of the liquid with the help of a rotating vane impeller. The positive displacement pumps operate by alternating between filling a cavity and displacing the volume of liquid in the cavity. The positive displacement pumps deliver a constant volume of liquid (for a given speed) against varying discharge pressure or head. By design, the positive displacement pumps are better suited to serve as an injection pump for a tracer study. Examples of positive displacement pumps include: rotary lobe, progressing cavity, rotary gear, piston, diaphragm, screw, and chemical metering pumps (e.g., bellows, diaphragm, piston, and traveling cylinder).

Selection of the most appropriate positive displacement pump depends upon the injection rate, the pressure in the receiving system, the chemical characteristics of the tracer, and local experience and preferences. Two types of positive displacement pumps have generally been used in tracer studies: gear pumps and metering pumps. The final selection depends upon viscosity of the tracer material, variability of pressure in the main, dosage accuracy needs, and other local factors. Furthermore, to control the drive speed (i.e., dosage), these pumps are equipped with alternating current (AC) or direct current (DC) motor. If a pump has an AC motor, frequency is adjusted; if it is equipped with a DC motor, voltage is adjusted to control speed.

EPA has used gear pumps equipped with variable frequency drives in the past with success for conducting tracer studies. Other studies have reported success with metering pumps with variable speed or variable stroke controllers. The pump should be sized in accordance with the anticipated tracer dosage (for more details, see Tracer Dosage and Injection Duration Section 3.2.3) and pressure range in the main pipe for the selected injection location(s) in the study area. Depending upon the location and dosage requirements, more than one size of pump may be needed (excluding backup pumps).

3.1.5.2 Tracer Storage and Dosage Rate Measurement

Tracers are available in dry or liquid form. If purchased as a powder, provisions for mixing the powder with water must be made. If the tracer is purchased in liquid form, it typically comes in either 55-gallon drums or in larger containers such as a 330-gallon tote. If only a small amount of tracer is needed, a single 55-gallon drum will typically suffice. For greater accuracy, it is recommended that the tracer be transferred from 55-gallon drums to a suitably sized day tank with a sight glass (used to periodically monitor the total tracer volume dosed). It is easiest to pump the tracer from a single container rather than having to switch the pump from container to container during the injection process. Details on tracer dosage calculations are presented in Section 3.2.3.

If a metering pump is purchased, care must be taken so that the pump flow rate is calibrated for the specific tracer solution (by the vendor). Furthermore, the

> During a tracer study when a tracer chemical is being injected into the system, in order to meet water quality regulations and to simplify the modeling, it may be desirable to maintain a constant tracer concentration in the receiving pipe. This can be accomplished by monitoring the resulting concentration in the receiving pipe and manually adjusting the tracer injection rate or through the use of a closed-loop system for automatically controlling the injection rate based on flow in the receiving pipe. The automated process is most effective at a location where the flow in the pipe is varying relatively slowly and where a flow meter exists. A typical situation is the use of an existing venturi meter that generates a 4-20 milli-ampere (ma) signal. This signal can be used as input to a controller that has been calibrated and programmed to control the stroke or speed of a variable stroke or speed injection pump. If the flow in the receiving pipe is varying rapidly over a large flow range, it is difficult for the closed-loop system to respond quickly.

variable area flow meters (rotameters - with floats contained in an upright conical tube) are relatively inaccurate for measuring tracer dosage even after adjustments are made for density and viscosity. Figure 3-1 shows a "flow tube" that can easily be custom fabricated and calibrated to accurately measure the rate of tracer injection. It is recommended that the supply tank also be marked to keep track of the tracer fluid level. Times should be noted at each mark so that it is possible to create a mass balance for the tracer injected during the study.

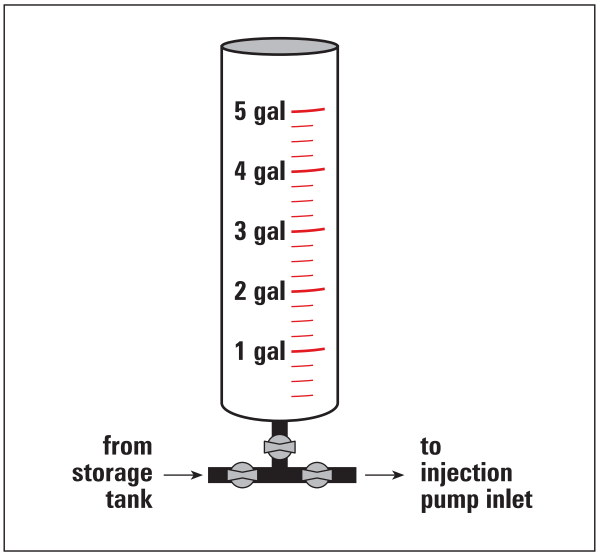


Figure 3-1. Flow Calibration Tube.

3.1.5.3 Distribution System Flow Rate Measurement

In order to calculate the concentration of the tracer in the receiving pipe, it is necessary to know the flow rate in the pipe, the injection rate of the tracer, the injected concentration of the tracer, and the background concentration in the water before tracer is added. Flow rate should be measured continuously, because variations in pipe flow rate can affect tracer concentration. These fluctuations in flow can be accommodated by manually adjusting the tracer injection rate in the field or through the use of a flow-paced injection pump that responds to the flow in the receiving pipe.

Placement of additional flow meters or other flow measuring devices at various points in the system is recommended. This information will be very useful during the post-tracer modeling studies and is invaluable in calibrating a network hydraulic model. If the existing system does not have an adequate number of flow meters for purposes of a tracer study, installation of additional meters is recommended.

Various types of flow meters may be used to measure flow in pipes. They are categorized as either non-intrusive or intrusive meters. Portable ultrasonic flow meters are non-intrusive and provide reasonably accurate data if the pipe material is conductive and relatively non-tuberculated. The ultrasonic flow meter requires suitable upstream/downstream straight runs of pipe. Insertion flow meters are also an option for measuring pipe flow rates. Insertion meters are intrusive, and may be magnetic (magmeters) that are flange coupled to the pipe or have propellers that must be inserted through a hole in the pipe. All meters require that the receiving main pipe be exposed (via excavation) or that an existing vault be used. If the injection location is in the vicinity of a reservoir/tank and the water level changes are available in real time, it may, in some instances, serve as a rough surrogate for in-pipe flow measurement. The selected method of flow measurement must be field tested.

> Depending upon the size of the reservoir/tank and the local demand, the reservoir level changes may not be fast or accurate and precise enough to determine the flow rate in real time.

3.1.5.4 Field Measurement of Tracer Concentration

Tracer concentration may be measured in the field using either automated monitors that analyze a sample at a preset frequency, by collecting "grab" samples, or a combination of both. Grab samples can be manually analyzed in the field or in the laboratory.

If grab sampling is used during a tracer study, the sampling team will generally traverse a circuit of several sampling locations. Using such an approach will generally yield a sampling frequency of one sample per station every one to three hours for an average-sized residential neighborhood (unless multiple crews are used). Some of the factors that will influence sampling frequency include the speed at which the tracer is moving within the distribution system, the number of sampling crews participating in the study, the number of sampling sites selected, the time of the day, and the distance between sampling sites. Equipment requirements for grab sampling are minimal and may include the following: coolers, ice, labeled sample bottles, log books, and temperature blanks. If samples are to be analyzed in the field, the sampling teams will need the appropriate analytical equipment. If samples are to be analyzed in the laboratory, the team will need the means to properly store and transport samples to a central laboratory. The quality assurance project plan (QAPP) may require duplicate or split samples for some or all of the primary samples. When taking a grab sample, care must be taken to flush the tap for a sufficient time to ensure that the sample is representative of the distribution main rather than the service lines.

Reliance solely on grab sampling may be impractical if the study area is large, the tracer front is moving rapidly, or a high frequency of sampling is desired. In these cases, continuous automated monitoring may be the best choice although some grab samples for quality assurance and quality control are recommended. If calcium chloride or sodium chloride is the tracer selected, an online specific-conductivity meter equipped with an associated data logger is recommended. Automated monitors are available if chlorine residual is used as a tracer. There are also automated monitors available if fluoride is used as a tracer, but there has been relatively limited use under field conditions. Since most automated monitors require a continuous side stream (rather than being inserted directly into a main), the drainage flow from the monitor must be discharged into a sewer, into the street and subsequently into a storm drain, or into a pervious area. This discharge can be an added complication during cold weather when it may freeze. Since this discharge stream is generally chlorinated or chloraminated, regulations may control discharge into natural water courses. Additionally, this discharge flow may have to be accounted for if the data set is being used to calibrate a distribution system model, and the quantity of discharge through a particular meter is significant relative to the demand in the vicinity of the meter. If the total drainage discharge is significant for the purposes of modeling, provisions for continuously or manually measuring the amount of flow being bypassed are needed.

Potential grab and online sampling sites include: dedicated sampling taps, hydrants, pump stations, tank inlet-outlet lines, and faucets located inside or outside of buildings. Figure 3-2 depicts an automated monitoring station used by EPA. This figure illustrates the case where the sampling tap is allowed to run continuously throughout the study with the water going to a drain. The flow rate to or through the sampling tap must be sufficient to minimize the travel time from the main to the monitor.

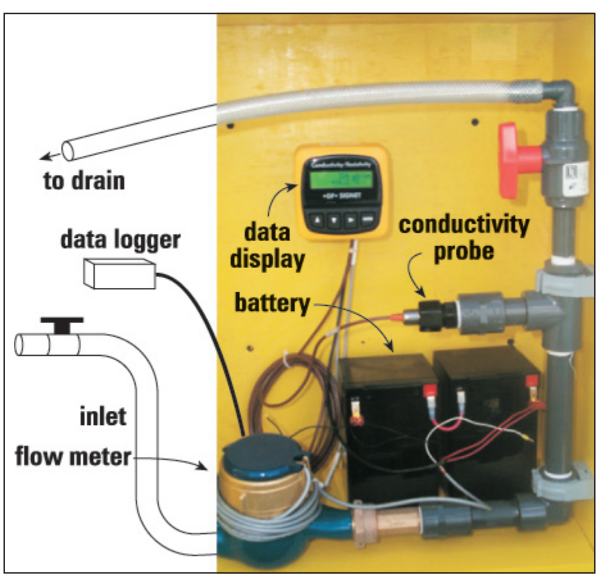


Figure 3-2. Automated Monitoring Station.

EPA and GCWW have pioneered the use of online monitors as a central focus for distribution system tracer studies. In a series of field tests, EPA and GCWW injected calcium chloride tracer into the water system and followed the movement of the tracer using automated conductivity meters strategically placed throughout the study area. Three separate studies were conducted in a large water system representing a small highly urbanized area, a small dead-end suburban area, and a large suburban pressure zone. Based on the success of these studies, similar tracer studies have been conducted utilizing a combination of online monitors and grab samples by the CDC using both fluoride and sodium chloride as tracers in Hillsborough County, Florida (Boccelli et al., 2004) and by the Agency for Toxic Substances and Disease Registry (ATSDR) using fluoride and calcium chloride at a large military base in North Carolina (Maslia et al., 2005; Sautner et al., 2005).

Online, automated sampling programs should be complemented with a grab sampling program to add a degree of confidence in measured data and to supplement field data at additional locations or at the automated monitor stations if they fail to record correctly.

3.1.6 Developing a Detailed Study Design

A key element in planning and designing a tracer study is the preparation of a study design document. This document serves as the overall plan for conducting a tracer study and thus, the roadmap for execution of the study. Three important study-specific parts of the design plan that may be required before the execution phase are a QAPP, a Health and Safety Project Plan (HSPP), and a contingency plan. The contingency plan describes the actions to be taken if unexpected events occur; for example, if distribution system concentrations of the tracer exceed the MCL for chloride or fluoride. The HSPP should at a minimum define the job hazards that might be encountered and the controls, protective equipment, sample handling and work practices, safety review procedures, and emergency procedures to be employed during the study.

The QAPP should clearly define the project objectives, organization, experimental approach, sampling procedures, analytical methods, protocols, instrument calibration requirements, data reporting, data reduction, and data verification procedures.

3.1.7 Addressing Agency and Public Notification

Appropriate agencies, including fire and police departments, should be notified prior to the commencement of field activities. With heightened awareness of security, all people participating should have a valid identification and contact information. A standard statement concerning the study should be developed and provided to all team members in case they receive inquires at the study site. This same statement should be used by utility personnel to answer any telephone inquires that might be received.

> A summary information card may be provided to the study participants that could be handed out to the public during the study (if requested). This minimizes the risks of mis-communication.

If the injection site or installation of meters requires excavation, the study team must obtain the necessary permits and approvals. This is especially important if any of the sites are in a residential neighborhood or near a busy street or road. Care should be taken in all cases to provide adequate traffic control. Safety is of paramount consideration.

3.2 Executing a Tracer Study

The team should first become familiar with the detailed study design documents discussed in Section 3.1.6. Based on these documents, there are several tasks that need to be completed during the execution phase of a tracer study. These tasks include:

- Procurement, setup, testing, and disinfection of study equipment (including pumps, storage tanks, chemicals, reagents, tubing, connectors, and continuous tracer monitoring stations).
- Installation of field equipment and testing (both flow and tracer monitoring equipment to confirm study-specific distribution system operation and flow stability).
- Tracer dosage and injection duration calculations.
- “Dry runs” and planned tracer injection events.
- Real-time field assessments, sampling, and analysis.
- Equipment demobilization, initiation of data collection, reduction, and verification process.

These specific execution subtasks are further discussed in the following sub-sections.

> A tailgate safety meeting before commencement of any field work is the best method to increase awareness.

3.2.1 Procurement, Setup, Testing and Disinfection of Study Equipment

Field equipment identified under Section 3.1.5 and its subsections should be procured on a timeline such that the items arrive several weeks before the planned study date, especially the monitoring and injection equipment that may require assembly. An early arrival will ensure that the equipment can be properly configured and tested before field use.

Unless pre-calibrated flow-paced injection equipment is purchased (or if the study does not require injection equipment – as in the case of using naturally/normally occurring tracers), the study team should obtain an appropriate injection pump setup. Figure 3-3 shows a picture of a tracer injection system used by EPA for field tests. This setup should be calibrated in the lab to compute the speed-specific dosage rate using the tracer solution. If appropriate, a flow-calibration tube should also be fabricated to confirm the flow in the field. Figure 3-3 also depicts a flow-tube used by EPA.

Figure 3-3. Tracer Injection Setup (Storage Tank, Calibration Tube and Feed Pump).

Concurrently, if applicable, the team should initiate the fabrication of the automated tracer monitoring stations. These stations are typically equipped with a probe for measuring the tracer (or a surrogate parameter such as conductivity), associated data logger, and batteries (for powering the probe and the data logger). If accurate measurement of flow through the automated monitoring station is needed, it should be augmented with a household-style water meter and logger. The equipment should be housed in a secure lock box to protect it during the field study. Figure 3-2 shows an automated monitoring station used by EPA and GCWW to conduct a tracer study. The entire setup should be tested in the lab to ensure proper operation and battery capacity to maintain uninterrupted operation.

The grab sampling, laboratory equipment, tracer storage tanks, transportation equipment, and arrangements should be procured and set up. The field equipment hookup, including interconnections between the tracer storage tank, injection pump, and flow-tube, should be leak tested. The equipment used for injection should be properly disinfected and tested prior to field deployment to ensure that no microbiological contamination results from the field tests.

If ultrasonic flow meters are procured for field deployment, the equipment should be set up in a lab environment to confirm the individual component operation and approximate battery life. The existing flow and data acquisition systems to be used in the field study should be sampled for data accuracy and field communication.

During the lab testing phase of the field equipment, the entire field (and backup) crew should familiarize themselves with proper operating procedures for the equipment they are designated to operate.

One procedure for equipment disinfection is to prepare approximately 50 gallons of 50 ppm chlorine disinfectant solution. This solution is then re-circulated through the injection pump setup for about 15 minutes. Thereafter, continuously flush the injection pump using de-ionized water for about 15 minutes. Collect a water sample at the end of the flush cycle and send it for bacteriological analysis (Coliform and E. coli) to insure that the disinfection procedure was successful. For the purposes of sampling, use sterile sample bottles with a de-chlorinating agent (e.g., sodium thiosulfate). The de-chlorinating agent is added to remove any residual chlorine or other halogen that may continue the disinfection process in the sample and yield incorrect test results.

3.2.2 Installation of Field Equipment and Testing

Prior to the commencement of field activity, a brief "tailgate" health and safety meeting should be conducted at the beginning of each day to remind the crew of potential job hazards. Mobilization of field equipment for excavations (if required – for installing main flow meters) should be initiated to allow for the flow monitoring devices to be installed prior to the scheduled injection event(s). This time lag will vary according to the needs of the specific study and could range from several days to several weeks. The early installation of flow meters will allow the study team to capture actual field flow data for performing any revisions to tracer dosage computations and preliminary hydraulic modeling analysis. The flow meter installation location should meet the manufacturer's recommendations for upstream and downstream straight lengths of undisturbed pipe. The excavations should be performed in accordance with the HSPP. Appropriate drainage for the excavated pits should be arranged in case rain is forecast during the study period.

The measured field flow data should be utilized to confirm the stability and range of flow at the injection location and other major branches of the system where flow is monitored. It may be necessary to operate the distribution system under specified conditions in order to achieve optimum results during the study. The operational changes that may be required include: scheduled cycling of tank levels, pumps, and valves. Time required for the deployment of the automated monitoring stations prior to the start of the tracer tests is dependent upon several factors, including the number of monitoring stations, the distances between stations, the ease of attaching the stations to the sampling hydrants, and the effort required to calibrate the monitoring equipment. If feasible and consistent with normal operating policies, the system should be operated to avoid frequent abrupt changes in flow such as would be associated with a pump that was cycling on and off very rapidly.

A day or two prior to the execution of the tracer injection event, the study team should fully deploy the continuous monitoring stations (if used). These stations should be hooked up at the designated sampling locations and data logs should be checked to ensure data are being collected. Flow through a monitoring station should be sufficient to minimize the time delay in detecting the injected tracer between the main and the sampling location. Experience has shown that 1 to 2 gallons per minute (gpm) is usually sufficient. The field crew should also test the coverage and reliability of field communication devices (such as cellular phones) in the designated study area.

3.2.3 Tracer Dosage and Injection Duration Calculations

Factors affecting the amount of tracer required for the study include the duration of the injection, the flow rate in the receiving pipe, and the target concentration in the distributed water. This target concentration should be consistent with drinking water standards. For example, if fluoride is being injected (into a system that does not fluoridate) with a secondary MCL of 2 mg/L, a reasonable target concentration level is 80% of the MCL, i.e., 1.6 mg/L. The injection rate should be set to meet that goal.

Using the principle of material balance, the resulting tracer concentration in a receiving pipe downstream of the point of injection can be calculated as follows:

$$Q_D = Q_U + Q_T \quad \text{(Equation 3-1)}$$

$$C_D = \frac{(C_B \bullet Q_U) + (C_T \bullet Q_T)}{Q_D} \quad \text{(Equation 3-2)}$$

Where

Q_D = flow downstream of injection point, L^3/T

Q_U = flow upstream of injection point, L^3/T

Q_T = flow of tracer solution, L^3/T

C_D = concentration of tracer material downstream of injection point, M/L^3

C_B = background concentration of tracer material in distributed water, M/L^3

C_T = tracer concentration, M/L^3

Equation 3-1 represents continuity and Equation 3-2 represents conservation of mass. As written, these equations are independent of units for mass (M), length (L), and time (T) as long as consistent units are used for computations. However, when tracer concentrations, injection rates, and injection duration are used to calculate the required volume of tracer material purchased, units for flow, concentration, and time must be commensurate or appropriate conversion factors must be employed.

For some tracers, the allowable concentration in the distributed water may be controlled by one of the dissolved ions that are part of the tracer. For example, if calcium chloride is the selected tracer, the concentration of the chloride ion in the distributed water controls the amount of tracer that may be injected.

Injection duration depends upon the size and complexity of the distribution system, and the modeling objectives of the study. A typical duration can range from one hour in a small or branched system, to eight hours or more in a larger, looped system. Some studies have reported success with a series of pulses. However, if the duration of the injection is too short or the series of pulses too close together in time, it is difficult to separate the tracer fronts as they traverse different paths at different velocities through the looped systems. The presence of tanks can also impact the needed tracer duration since active filling and drawing can dampen the resulting tracer concentration as it moves through the system.

The injection equipment should be located close to the main in order to minimize the tracer travel time to the main. Alternatively, the travel time should be compensated for during the appropriate phases of the study evaluation.

3.2.4 Dry Runs and Planned Tracer Injection Event(s)

Before the planned full-scale tracer injection event is actually carried out, the project team should consider conducting a smaller duration dry run injection to confirm the system operation and expected levels of tracer concentration. If continuous monitors are to be used in the study, then during the dry run some or all of the monitors should be installed and tested. The timing and duration of the dry run should be such that the injected pulse should be short and clear the system well before the actual event is initiated.

The dry run serves as a final systems check and provides the study team an opportunity to make any necessary last minute changes prior to the actual study. Thereafter, the actual full-scale injection event should be conducted as planned.

3.2.5 Real Time Field Assessments, Sampling, and Analysis

While the injection event is ongoing, the study team should carefully monitor the tracer concentration at the immediate downstream location of the injection to ensure that there are no significant deviations in the expected versus observed concentrations in the field. Field crews should communicate directly with the system operations. It is critical that the field personnel are aware of any changes in system operations that may affect the study. Unanticipated changes in water demand may cause the tracer concentration to exceed target concentration levels. In such an event, the field crew should be trained to take measures to minimize any adverse effects. The preventive measures may include lowering (or stopping) the injection rate, or achieving appropriate dilution by means of rerouting water through the distribution system (as appropriate). Furthermore, any such tracer concentration exceedances should be confirmed by performing field grab sample analysis to make sure that the exceedance is real and not an instrument anomaly. Until the results are confirmed, it is best to err on the safe side and take preventive measures to maintain water quality.

Periodically, the field crew should take grab samples and inspect the continuous monitoring stations to ensure that the equipment is operating properly. The grab samples should be appropriately handled and analyzed in the field or transported to the laboratory for further analysis. The sampling and monitoring effort should continue well past the conclusion of the injection event until the tracer is expected (and observed) to have moved out of the system. This may take a period of 24 to 48 hours or more after completion of the injection event.

During the course of the sampling event, it is very useful to examine and assess the field data on a near real-time basis. Questions that should be asked include "Are the results reasonable?" "Is the tracer moving through the system at a speed consistent with predictions?" Based on this assessment, modifications may be made in terms of injection rate, grab sampling frequency, or study duration.

3.2.6 Equipment De-Mobilization, Initiation of Data Collection, Reduction, and Verification Process

After the scheduled injection event(s) are completed, the field crew should download the data (including flow and tracer concentrations) from the various monitoring devices. The data should be spot checked against field grab sampling data to ensure that there are no time anomalies or gaps in the data log and the readings match relatively well.

After the field sampling events are completed, the crew should de-mobilize the equipment, remove the automated monitoring stations, refill any excavations, and restore the system operations to their normal conditions.

Downloaded data from the field should be processed according to the QAPP and used for further modeling and analysis. The use of field data in calibration and validation of hydraulic and water quality models is discussed further in Chapter 4.

3.3 Tracer Study Costs

In general, the cost of conducting a tracer study is proportional to the study area size, number of monitoring sites, study duration, sophistication and amount of equipment, and complexity of post-study analysis. If a study incorporates an injected tracer and the use of continuous monitors, it can be much more expensive initially than a study using a natural tracer and grab samples. However, the injection equipment and continuous monitoring equipment can be reused at various locations. These are the cost tradeoffs between purchase of automated monitoring equipment and labor associated with grab sampling. In some cases, a larger dataset derived from an automated monitor is necessary for a detailed analysis. Cost data presented in this section are intended to provide the basis for this type of analysis. For the purposes of this chapter, the overall costs have been broken down into two distinct categories: equipment and labor. Material costs are only a fraction of the total, and therefore, have been combined and included with equipment costs for simplicity.

Table 3-2 lists typical equipment and material costs for those items that may be used in tracer studies. The unit costs can be easily scaled to the needs of a specific study. Chemical tracer costs, including analytical costs, were provided earlier in Table 3-1.

Costs may vary widely among studies. For example, if it is necessary to purchase or rent a storage tank or a

Table 3-2. Equipment Costs

Equipment & Material	Unit Cost ($)
Injection pump	$1,000 - $5,000
Flow meter (ultrasonic meter for main pipes)	$7,000 - $9,000
Excavation, rigging and backfill (equipment rental per site)	$1,500
Lab chemicals, batteries and plumbing supplies (lump sum*)	$1,000 - $5,000
Automated monitoring box (self constructed)	< $200
Online conductivity ISE, meter and logger	$800 - $1,500
Automated monitoring station water flow meter	$600 - $800
Online fluoride meter	$5,000 - $10,000
Safety equipment (e.g., vests, first aid kits, rain gear, and flashlights)	$500 - $1,000
Communication equipment (e.g., radios and GPS)	$500 - $1,000
Hydrant equipment (e.g., wrenches, caps, and hoses)	$1,000 - $2,000
Transportation (e.g., rental vehicles)	$500 - $2,000
Tracer storage tanks (depending upon volume and material)	$500 - $1,000

truck, costs will be higher if these types of items are not readily available. If the study team elects to analyze samples in-house rather than using an outside laboratory, the team should balance the cost of labor, and the cost of additional reagents and chemicals against the cost of performing the analyses at an outside commercial laboratory. Labor costs may be even more variable than equipment and material costs and are a function of the size and complexity of the study. In order to provide an easy basis for comparison, the labor costs are presented in labor hours (Table 3-3) and include a combination of engineers and technicians. Labor hours have been estimated for low, medium, and high-end studies. These estimates are obtained from actual field studies, as described below. This approach should allow utilities to make site-specific cost estimates.

Table 3-3. Representative Labor Hours for a Range of Studies

Activity	Low-End	Medium	High-End
Planning	27	274	480
Setup	-	150	520
Field study	51	604	370
Laboratory analysis	8	160	120
Post-study assessment	24	212	740
Total	110	1,400	2,230

A typical example of a low-end tracer study is provided by the Sweetwater Authority distribution system in Southern California (see second sidebar in Section 3.1.4.5, page 3-6). The Sweetwater system covers a service area of 28 square miles. The utility was able to take advantage of a naturally occurring tracer and used grab samples taken at 28 existing dedicated sampling sites over a period of 5 days. A study performed in the 21-square-mile Cheshire service area of the South Central Connecticut Regional Water Authority in 1989 (see second sidebar in Section 3.1.4.1 on page 3-4) provides an example of a medium-level tracer study. In this case, the normal fluoride feed was shut off for a period of 7 days (and then turned back on) and grab samples were taken at intervals of a few hours at 23 sites over a period of 14 days. An example of a high-end study is provided by a two-phased field investigation conducted in two suburban areas of GCWW. The first area is a small (<1 square mile) dead-end system, and the second area, a 12-square-mile pressure zone. A calcium chloride tracer was injected and monitored using a combination of automated conductivity meters and grab samples. In the smaller area, 20 meters were used and monitoring was conducted over a 24-hour period. In the second area, 33 meters were used and two separate tracer injections were conducted over a period of 5 days. Including both studies, a total of 725 grab samples were taken and analyzed for conductivity, chloride, and calcium. Flow was monitored at four locations using ultrasonic flow meters.

Table 3-3 presents estimated labor hours for these types of studies. They are divided into the planning phase (as described in Section 3.1); setup, field work, and laboratory analysis that together make up the execution phase (see Section 3.2); and the post-study modeling, assessment, and report phase. As illustrated in this table, there is a significant variation in the labor hours required to conduct a tracer study. For example, the low-end labor costs resulted due to the following study characteristics: naturally occurring tracer was used, no new equipment was purchased, existing routine monitoring sites were used, and only a limited post-study assessment was made. The medium-sized study included the following characteristics: a chemical that was routinely added (fluoride) to the water distribution system was used as the tracer (by shutting it off), the study required a much longer period to complete, and since it was the first major tracer study in the distribution system, it required significant planning. The high-end study included the following characteristics: it was the first major tracer study employing wide-scale use of continuous monitors; a non-naturally occurring, non-routinely added chemical was injected as a tracer; and significant time was required for acquiring and installing the equipment. For purposes of this study, a very detailed post-study data assessment involving processing of tracer study data, pipe network model calibration and report preparation required significant labor expenditures. Examples of model calibration efforts associated with tracer studies are presented in Chapter 4.

3.4 Summary, Conclusions and Recommendations

Tracers and tracing techniques have been used for many years in a number of engineering applications to estimate stream velocity and retention time in water and water supply unit processes. More recently, tracers have been used for calibrating drinking water distribution system hydraulic and water quality models. For the purposes of this document, it is assumed that tracer studies are used to calibrate and validate network models. The calibrated and validated network models are then used to estimate other parameters such as water age and travel times. However, the data from a tracer study can be directly used to estimate some specific parameters such as water age (DiGiano et al., 2005). A comprehensive summary of potential uses and regulatory applications for tracer studies is provided in the first subsection of this chapter. Drinking water tracers might include chemicals that are injected into a water distribution pipe, the temporary shutoff of a chemical additive currently being added to treated water (such as fluoride), or significant changes in concentration of disinfectants, DBPs, or natural compounds. The tracer methodology selected would significantly impact the overall costs of the study. Probably, the most expensive option would be to inject a chemical tracer, monitor it using leased or purchased online instrumentation, and conduct the study using contractor staff. The least expensive approach would be to take advantage of a natural tracer, monitor the progress of the tracer by grab sampling, and conduct the study using primarily in-house staff. Once a tracer "injection" methodology has been selected, careful planning and execution will ensure the success of the study.

When planning a tracer study, if the specific steps outlined in this chapter are followed, they should greatly increase the potential for a successful study. These steps include: establishing clear study objectives, forming a study team, defining the study area characteristics, carefully selecting an appropriate tracer, selecting the proper field equipment, developing key planning documents, and ensuring that the public and affected agencies are notified. Application of a distribution and water quality model during the planning stage is highly recommended to simulate the approximate behavior that will be expected during the actual tracer event.

During the execution phase of the study, the following issues should be addressed: procurement of equipment and materials; setup, testing and disinfection of the procured equipment; availability of analytical instrumentation and laboratory facilities; and, finally, the installation, testing, and operation of field equipment. During the execution phase, it is important to review and understand how tracer dosages and injection duration are to be implemented. Dry runs are highly recommended as a means of debugging the procedures prior to a full study.

Distribution system tracer studies have been conducted for over 15 years, but recent technology developments have improved the efficiency of these studies and provide promise for greatly expanded applications in the future. Specific components that will fuel this expanded use include the following: continuous monitors that can be easily adapted for use in distribution systems are being developed and tested, in part in response to water security concerns; automated meter reading (AMR) equipment is being installed by many utilities and could provide more detailed temporal and spatial consumption data for hydraulic models; advanced analysis software is evolving that will facilitate the use of large amounts of continuous data in calibrating distribution system models; and with increased availability of these technologies, costs are expected to decrease so that larger utilities can afford to purchase and routinely use the equipment, and consulting engineers can affordably offer these services to smaller utilities.

During the field study, it is important that the study team be able to assess the progress of the tracer, in real time, as it propagates through the system. Concise and consistent communications between tracer study team members, test coordinator, and water utility staff, is critical al all times during the test.

In the future, it is highly likely that advances currently on the horizon will result in significant increased use of both online tracer (or water quality) monitors and flow monitoring instrumentation. As the on-line technology becomes more widely used in drinking water, the use of network water quality models will also be more widely accepted. Online monitoring in conjunction with water quality modeling will provide an in-depth understanding of the manner in which water quality changes can be monitored in a drinking water distribution system. Also, given the current climate of concern over distribution water quality from both a regulatory and security viewpoint, it is reasonable to assume that there will be increased interest in applying this type of technology in the water industry.

References

Boccelli, D.L., F. Shang, J. G. Uber, A. Orcevic, D. Moll, S. Hooper, M. Maslia, J. Sautner, B. Blount, and F. Cardinali. "Tracer Tests for Network Model Calibration." Proceedings, ASCE-EWRI Annual Conference. 2004.

Boccelli, D., and J. Uber. "Incorporating Spatial Correlation in a Markov Chain Monte Carlo Approach for Network Model Calibration." Proceedings, ASCE-EWRI World Water & Environmental Resources Congress, Anchorage, AK. 2005.

Boulos, P.F., W.M. Grayman, R.W. Bowcock, J.W. Clapp, L.A. Rossman, R.M. Clark, R.A. Deininger, and A.K. Dhingra. "Hydraulic Mixing and Free Chlorine Residuals in Reservoirs," *Journal of AWWA*, 88(7):48-59. 1996.

Clark, R.M., W.M. Grayman, R. Males, and A. F. Hess. "Modeling Contaminant Propagation in DrinkingWater Distribution Systems," *Journal of Environmental Engineering, ASCE*, 119(2):349-364. 1993.

Clark, R.M., W.M. Grayman, J.A. Goodrich, R.A. Deininger, and A.F. Hess. "Field Testing Distribution of Water Quality Models," *Journal of AWWA*, 83(7):67-75. 1991.

Clark, R.M., G. Smalley, J.A. Goodrich, R. Tull, L.A. Rossman, J.T. Vasconcelos, and P.F. Boulos. "Managing Water Quality in Distribution Systems: Simulating TTHM and Chlorine Residual Propagation," *Journal of Water Supply Research and Technology – Aqua*, 43(4):182-191. 1994.

Clark, R.M., and J.A. Coyle. "Measuring and Modeling Variations in Distribution System Water Quality," *Journal of AWWA*, 82(8):46-53. 1990.

DiGiano, F.A., and G. Carter. "Tracer Studies to Measure Water Residence Time in a Distribution System Supplied by Two Water Treatment Plants." Proceedings, AWWA Annual Conference. 2001.

DiGiano, F.A., W. Zhang, and A. Travaglia. "Development of the mean residence time from tracer studies in distribution systems." *Journal of Water Supply: Research and Technology - Aqua* 54:1-14. 2005.

EPA. *The Stage 2 DBPR Initial Distribution System Evaluation Guidance Manual.* 2003a.

EPA. *Drinking Water Advisory: Consumer Acceptability Advice and Health Effects Analysis on Sodium.* Available at: http://www.epa.gov/safewater/ccl/pdfs/reg_determine1/support_cc1_sodium_dwreport.pdf. 2003b.

Ferguson, B.A. and F.A. DiGiano. "Impact of temporary switches from monochloramine to free chlorine on water quality in distribution systems." Proceedings, AWWA Annual Conference. 2005.

Grayman, W.M., R.A. Deininger, A. Green, P.F. Boulos, R.W. Bowcock, and C.C. Godwin. "Water Quality and Mixing Models for Tanks and Reservoirs," *Journal of AWWA*, 88(7):60-73. 1996.

Grayman, W.M., L.A. Rossman, C. Arnold, R.A. Deininger, C. Smith, J.F. Smith, and R. Schnipke. *Water Quality Modeling of Distribution System Storage Facilities.* AwwaRF and AWWA. Denver, CO. 2000.

Grayman, W.M. "Use of Tracer Studies and Water Quality Models to Calibrate a Network Hydraulic Model," *Current Methods*, 1(1):38-42, Haestad Press, Waterbury, CT. 2001.

Grayman, W.M., L. A. Rossman, R. A. Deininger, C. D. Smith, C. N. Arnold, and J. F. Smith. "Mixing and Aging of Water in Distribution System Storage Facilities," *Journal of AWWA*, 96(9):70-80. 2004.

Hatcher, M.D., W. M. Grayman, C. D. Smith, and M. Mann. "Monitoring and Modeling of the Sweetwater Authority Distribution System to Assess Water Quality." Proceedings, AWWA Annual Conference. 2004.

Maslia, M.L., J.B. Sautner, C. Valenzuela, W.M. Grayman, M.M. Aral, and J.W. Green, Jr. "Use of Continuous Recording Water-Quality Monitoring Equipment for Conducting Water-Distribution System Tracer Tests: The Good, the Bad and the Ugly." Proceedings, ASCE-EWRI World Water & Environmental Resources Congress, Anchorage, AK. 2005.

Panguluri, S., R. Krishnan, L. Garner, C. Patterson, Y. Lee, D. Hartman, W. Grayman, R. Clark and H. Piao. "Using Continuous Monitors for Conducting Tracer Studies in Water Distribution Systems." Proceedings, ASCE-EWRI World Water & Environmental Resources Congress, Anchorage, AK. 2005.

Sautner, J.B., M.L. Maslia, C. Valenzuela, W.M. Grayman, M.M. Aral, and J.W. Green, Jr. "Field Testing of Water Distribution Systems at U.S. Marine Corps Base, Camp Lejeune, North Carolina, in Support of an Epidemiological Study." Proceedings, ASCE-EWRI World Water & Environmental Resources Congress, Anchorage, AK. 2005.

AWWA. *Standard Methods for the Examination of Water and Wastewater, 20th Edition.* Edited by: Lenore S. Clrsceri, Arnold E. Greenberg, and Andrew D. Eaton, American Pubic Health Association/AWWA/ Water Environment Federation, pp 2-44 to 2-45. 1998.

Teefy, S.M., and P.C. Singer. "Performance Testing and Analysis of Tracer Tests to Determine Compliance of a Disinfection Scheme with the SWTR." *Journal of AWWA*, 82(12):88-98. 1990.

Teefy, S.M. *Tracer Studies in Water Treatment Facilities: A Protocol and Case Studies.* AwwaRF and AWWA, Denver, CO. 1996.

Vasconcelos, J.J., L.A. Rossman, W.M. Grayman, P.F. Boulos, and R.M. Clark. "Kinetics of Chlorine Decay," *Journal of AWWA*, 89(7):54-65. 1997.

Vasconcelos, J., P. Boulos, W. Grayman, L. Kiene, O. Wable, P. Biswas, A. Bahri, L. Rossman, R. Clark, and J. Goodrich. *Characterization and Modeling of Chlorine Decay in Distribution Systems.* AwwaRF. 1996.

Chapter 4
Calibration of Distribution System Models

Water distribution system models can be used in a wide variety of applications to support design, planning, and analysis tasks. Since these tasks may result in engineering decisions involving significant investments, it is important that the model used be an acceptable representation of the "real world" and that the modeler have confidence in the model predictions. In order to determine whether a model represents the real world, it is customary to measure various system values (e.g., pressure, flow, storage tank water levels, and chlorine residuals) during field studies and then compare the field results to model predictions. If the model adequately predicts the field measurements under a range of conditions for an extended period of time, the model is considered to be calibrated. If there are significant discrepancies between the measured and modeled data, further calibration is needed. There are no general standards for defining what is adequate or what is a significant discrepancy. However, it is recognized that the level of calibration required will depend on the use of the model. A greater degree of calibration is required for models that are used for detailed analysis, such as design and water quality predictions, than for models used for more general planning purposes (e.g., master planning).

All models are approximations of the actual systems that are being represented. In a network model, both the mathematical equations used in the model and the specific model parameters are only numerical approximations. For example, the Hazen-Williams equation used to describe friction headloss is an empirical relationship that was derived based on laboratory experiments (Williams and Hazen, 1920). Furthermore, the roughness parameter (C-factor) used in the Hazen-Williams equation that modelers assign to each pipe is not known with total certainty because it is not feasible to examine and test every pipe in the system. The goal in calibration is to reduce uncertainty in model parameters to a level such that the accuracy of the model is commensurate with the type of decisions that will be made based on model predictions.

The types of model calibration associated with water distribution system analysis can be categorized in several ways. The nomenclature depends upon the adjusted parameters and the technique employed. In general, calibration can be categorized (or referenced) as follows:

- Hydraulic and water quality model calibration.

The concept of calibration can be compared to fine tuning an old fashioned television (TV) set. One knob on the TV is used for tuning the channel while other knobs are adjusted to improve color, sharpness, contrast, and hue. However, in calibrating a network model, there are far more knobs to adjust as illustrated in Figure 4-1.

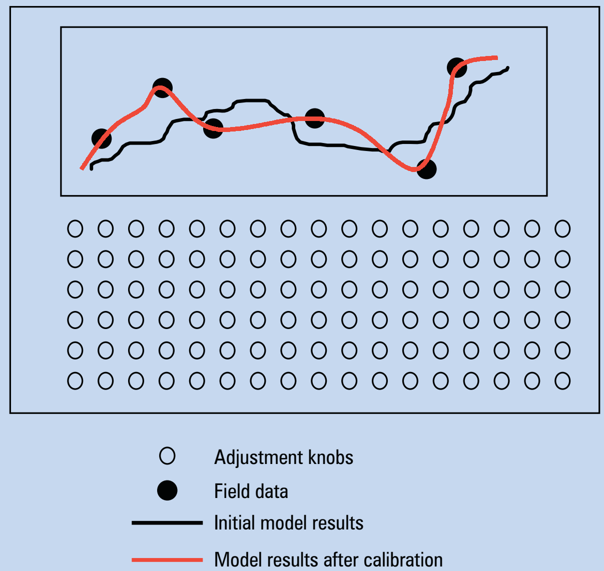


Figure 4-1. Conceptual Representation of Calibration.

Some of the knobs may be used to adjust roughness coefficients for pipes, other knobs to adjust demands assigned to nodes, while still other knobs may control valve positions, pump curves, or other parameters that are not known with complete certainty. Calibrating a model is an arduous task because there are many knobs that can be adjusted. Finding the combination of parameters that results in the best agreement between measured and modeled results is difficult. This process is complicated by the fact that there may not be a single best set of parameters. Extending the TV analogy, the knobs may be adjusted in order to get the best reception for one channel. However, when the channel is changed, the knobs may need to be adjusted to improve the reception for the new channel. Similarly, with a network model, a set of parameters may give the best match for one set of data while other parameters may give better results for another set of data. Therefore, it is recommended that a modeler first calibrate the model using one or more sets of field data and then validate it with an independent set of field data.

- Static (steady state) or dynamic (extended period simulation) calibration.
- Manual or automated calibration.

Hydraulic calibration refers to the process of adjusting the parameters that control the hydraulic behavior of the model. Similarly, water quality calibration relates to the process of adjusting parameters used in the water quality portion of the model. Static or steady-state calibration relates to calibration of a model that does not vary over time, or using data that is collected representing a snapshot in time. Dynamic or EPS calibration uses time-varying data in the calibration process. Manual calibration relies upon the user to investigate the effects of a range of possible parameter values. Automated calibration employs optimization techniques to find the set of parameters that results in the "best" match between measured and modeled results.

It should be noted that the specific application method and availability of some of these techniques will vary depending upon the software used for modeling and the available network model information. Therefore, only the general techniques employed in each of these types of calibration are discussed in the following sections. Then, some example case studies are presented to illustrate their use. The final section in this chapter discusses future trends in calibration and the possibility of general calibration standards.

4.1 Hydraulic and Water Quality Model Calibration

Hydraulic calibration is essential for any model simulation to be meaningful. Furthermore, the distribution system water quality models work in concert with the hydraulic model and utilize the flow and velocity information calculated by the hydraulic model. Thus, if the hydraulic model is not properly calibrated and results in inaccurate flow and velocity estimates, the water quality model will not perform correctly. In fact, water quality modeling is very sensitive to the underlying hydraulic model. Frequently, a hydraulic model that has been calibrated sufficiently for applications such as master planning may require additional calibration before it is appropriate for use in water quality modeling. The following subsections describe the parameters and techniques employed for hydraulic and water quality model calibration.

4.1.1 Hydraulic Model Calibration

Hydraulic behavior refers to flow conditions in pipes, valves and pumps, and pressure/head levels at junctions and tanks. Parameters that are typically set and adjusted include pipe roughness factors, minor losses, demands at nodes, the position of isolation valves (closed or open), control valve settings, pump curves, and demand patterns. When intially establishing and adjusting these parameters, care should be taken to keep the values for the parameters within reasonable bounds. For example, if local experience shows that the roughness factor for a 20-year old ductile iron pipe typically falls within a range from 100 to 130, a value that is not within or close to that range should not be used just to improve the agreement between the measured and modeled data. Use of unreasonable values may lead to a better match for one set of data, but will typically not provide a robust set of parameters that would apply in other situations.

Proper calibration requires that adjustments be made to the correct parameters. A common mistake occurs when adjustments are incorrectly made in one set of parameters in order to match the field results while the parameters that are actually incorrect are left untouched. This process is referred to as "compensating errors" and should obviously be avoided. Field verification of suspect parameters (e.g., open or closed valves) can reduce confusion created by compensating errors.

> An example of compensating errors is an adjustment in roughness factors in order to compensate for a closed isolation valve in the system that is represented as open, or partially open, in the model. In this case, unreasonably low values for the Hazen-Williams roughness coefficients are typically introduced in order to force a large headloss in the pipes that are actually closed. Though this may result in approximating the pressure measurements made in the field, it will introduce other errors in flow and velocity calculations. Compensating errors may also result from incorrectly adjusting demands or other parameters.

4.1.2 Water Quality Model Calibration

Subsequent to the proper calibration of a hydraulic model, additional calibration of parameters in a water quality model may be required. The following parameters are used by water quality models that may require some degree of calibration:

- Initial Conditions: Defines the water quality parameter (concentration) at all locations in the distribution system at the start of the simulation.
- Reaction Coefficients: Describes how water quality may vary over time due to chemical, biological or physical reactions occurring in the distribution system.
- Source Quality: Defines the water quality characteristics of the water source over the time period being simulated.

The details of calibration depend upon the type and application of the water quality model. Calibration requirements for each type of modeling are described below and summarized in Table 4-1.

Table 4-1. Calibration/Input Requirements for Water Quality Models

Model Application	Initial Conditions	Reaction Coefficients	Source Quality
Water age	YES	NO	Usually NO
Source tracing	YES	NO	Usually NO
Conservative constituent	YES	NO	YES
Reactive constituent	YES	YES	YES

- Water age: No explicit water quality calibration can be performed because there are no reaction coefficients. Estimates of initial water age in tanks and reservoirs are desirable in order to shorten the length of the simulation. Source water age is usually set to zero for all sources. Water age can be especially sensitive to inflow-outflow rates for tanks, mixing characteristics of tanks, and travel times in dead-end pipes.

When modeling a tank, an important parameter is the initial age of the water in the tank at the start of the simulation. This value cannot be measured in the field but can be estimated by dividing the tank volume by the volume of water that is exchanged each day. Frequently, modelers will just assume that the initial age is zero and run the model for a long period until it has reached a dynamic equilibrium. This occurs when the initial water in the tank has been flushed out entirely through the fill and draw process. The following figure (Figure 4-2) shows the effects of the initial water age on the modeled results. As illustrated, a good initial estimate for water age (120 hours in this case) results in a much shorter time period until the dynamic equilibrium is reached. In fact, in this case when the initial age was input as zero hours, the model did not even come close to reaching dynamic equilibrium during the simulation period and would have required a much longer run duration to reach the same point.

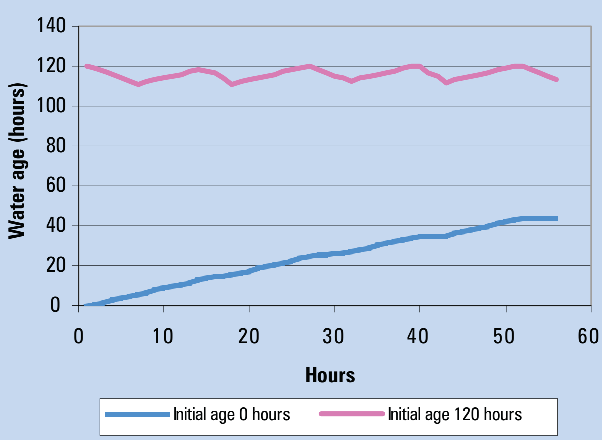


Figure 4-2. Effects of the Initial Water Age on the Modeled Results.

- Source tracing: No explicit water quality calibration can be performed because there are no reaction coefficients. Estimates of initial conditions in tanks for percentage of water coming from a source are desirable in order to shorten the length of the simulation. Values for sources are usually set to zero for all sources except for the specific source being traced.

- Conservative constituents: No explicit water quality calibration can be performed because there are no reaction coefficients. Estimates of initial conditions in tanks for concentrations of the conservative constituents can usually be determined from field data and are desirable in order to shorten the length of the simulation. Values for sources are set to the typical concentrations found in the source.

- Reactive constituents: For reactive constituents, both the form of the reaction equation and the reaction coefficients must be provided. When modeling chlorine or chloramine decay, the most common formulation is a first order decay equation including both bulk and wall decay coefficients. Values for these coefficients typically require laboratory and field analysis and calibration in order to match model results to the concentrations measured in the field. Correspondingly, THMs, a group of DBPs formed when water is chlorinated or chloraminated, generally increase in concentration with time (Vasconcelos et al., 1996). This process is frequently represented as a first order growth function that asymptotically approaches a limiting value representative of maximum concentration reached when all of the NOM has reacted or all of the chlorine has been consumed. Both the limiting value and the rate of growth must be determined in this case.

Water quality modeling is very sensitive to the hydraulic representation of the system. To reiterate, hydraulic calibration that may be sufficient for some hydraulic simulation may require additional calibration when used as a basis for water quality modeling.

4.2 Static Calibration and Dynamic Calibration

Just as water distribution system models can be run in a steady-state or an extended period mode, calibration can be performed in either a static mode using a steady-state model or in a dynamic mode using an extended period model. A common approach is to perform a static calibration first followed by EPS, to enhance the static calibration through a dynamic calibration. The options and procedures for these two types of calibration are described below.

4.2.1 Steady-State Calibration Methods

The two most common approaches used in calibrating a steady-state hydraulic model are C-factor tests and fire-flow tests. For water quality models of chlorine/chloramines, a test procedure for estimating bulk and wall demand may be employed. In all of these cases, field data is collected under controlled conditions and then applied to determine the model parameters that result in the best fit of the model to the field data.

4.2.1.1 C-Factor Tests

C-factor tests (sometimes called head loss tests) are performed to estimate the appropriate C-factors to be used in a hydraulic model. The C-factor represents the roughness of the pipe in the widely used Hazen-Williams friction equation. Typically, such tests are performed on a set of pipes that are representative of the range of pipe materials, pipe age, and pipe diameters found in the water system that is being studied. The results of the tests are then used to assign C-factors for other pipes of similar characteristics.

In a field test, a homogeneous section of pipe between 400 and 1,200 feet long is initially isolated. Subsequently, flow, pipe length, and head loss are measured in the field. Typically, nominal pipe diameters are taken from system maps and these values are used along with flow rate to calculate velocity. There are two alternative methods for determining head loss in the pipe section: a two-gage method (Figure 4-3) and a parallel hose method (Figure 4-4). With the two-gage method, pressure is read at hydrants located at the upstream and downstream end of the section and used along with elevation difference between the ends to calculate head loss. With the parallel hose method, a small-diameter hose is used to connect the two hydrants to a differential pressure gage to directly measure the difference in pressure. The two end hydrants should be spaced far enough apart and there should be sufficient flow so that there is a pressure drop of at least 15 pounds per square inch (psi) for a two-gage test or a 3-psi pressure drop for a parallel hose test (McEnroe et al., 1989). In both cases, a hydrant downstream of the test section is opened to induce flow and a sufficient pressure drop. Multiple downstream hydrants may also be employed to induce a greater flow and larger pressure drop. Typically, a pitot gage (as shown in Figures 4-3 and 4-4) is attached to the flowing hydrants to measure the flow rate. It is important to ensure that all flow between hydrants is accounted for (i.e., any connections that may bleed water into or out of the test section). The two-gage method is the more commonly used approach. The parallel hose method requires more

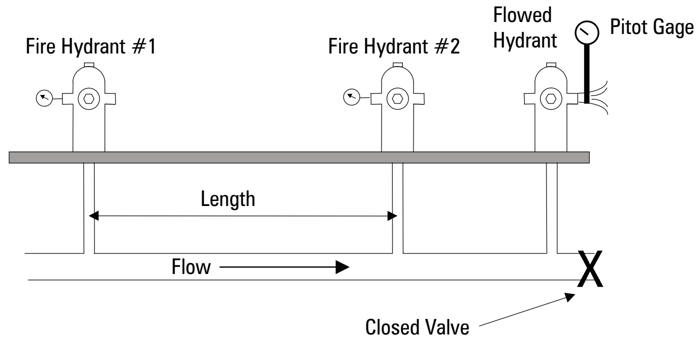


Figure 4-3. Schematic of Standard Two-Gage C-Factor Test Setup.

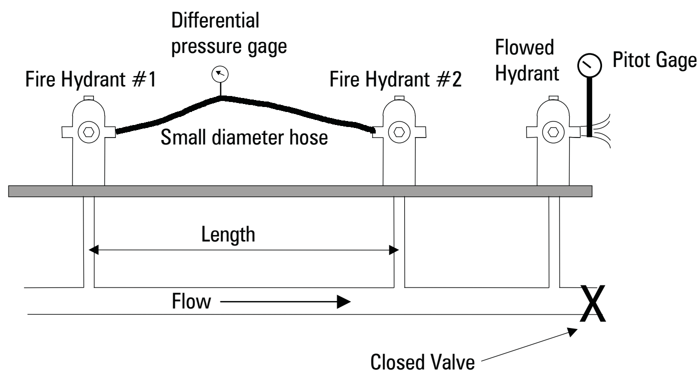


Figure 4-4. Schematic of Parallel Hose C-Factor Test Setup.

The underlying concept for a C-factor test is that all factors in the Hazen-Williams friction equation can be measured in the field and the equation can then be solved for the unknown C-factor. It can also be used to account for minor losses that occur through distribution system components (e.g., valves, fittings). The following equation is the Hazen-Williams equation (Equation 2-3) arranged to solve for roughness.

$$C = 8.71\ V\ D^{-0.63}\ (H/L)^{-0.54} \qquad \text{(Equation 4-1)}$$

where
C = roughness factor
V = velocity in feet per second
D = pipe diameter in inches
H = head loss in feet
L = pipe length in feet

specialized equipment, but is inherently more accurate and may be used when a large pressure drop cannot be achieved. Note that the valve is closed downstream of the flowing hydrant.

As noted above, an assumption is made that the pipe diameter has not diminished from its original nominal diameter due to tuberculation on the pipe walls. If that assumption is not valid, the calculated C-factors will be lower than expected. If very low C-factors are calculated based on a field C-factor test, it is recommended that further actions be taken in order to determine the effective diameter of representative pipes. These actions could include direct inspection of sample pipes or use of calipers inserted into the pipe to measure the effective pipe diameter.

4.2.1.2 Fire-Flow Tests

Fire-flow tests are routinely performed by water utilities to determine the ability of the system to deliver large flows needed to fight fires. In such a test, fire hydrants are opened, the flow through the hydrants measured and pressures measured at adjacent hydrants (see Figure 4-5). The high demands caused by the open hydrants lead to high flows and increased head loss in pipes in the area around the hydrants. Under these conditions, the system is stressed and the capacity of the system to deliver these flows is very sensitive to the roughness of the pipes.

These fire-flow tests can also be very effective as a calibration methodology. In this case, in addition to the standard information routinely collected as part of a fire-flow test (flows and pressures), information is collected on the general state of the system such as pump and valve operation, tank water levels, and general system demand. The distribution system model is then run under the system conditions observed during the test and adjustments made in roughness factors (or other parameters) so that the model adequately represents the data measured in the field.

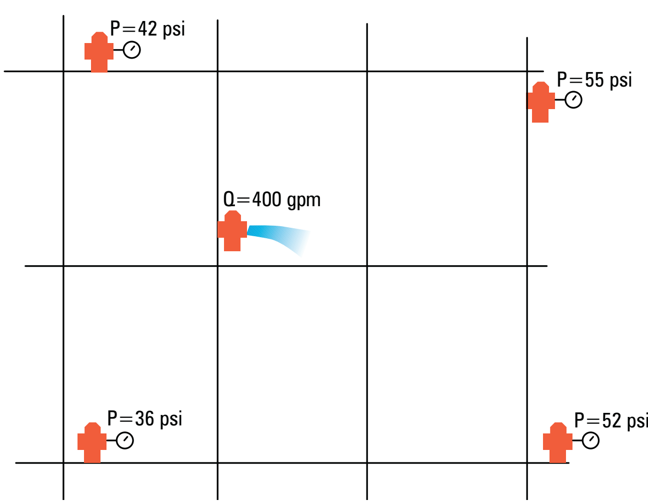


Figure 4-5. Fire-Flow Test Setup.

Figure 4-6. A Hydrant Being Flowed with a Diffuser as Part of a Fire-Flow Test.

Figure 4-6 illustrates an example setup for a fire-flow test. The diffuser attached to the hydrant in the figure includes a pitot gage used to measure the flow. The cage diffuses the flow and prevents any objects in the stream from being projected out at high speed.
In the case shown in Figure 4-5, only a single hydrant is opened, with the flow measured at that hydrant and pressure measurements made at four hydrants. Additional hydrants may be flowed and monitored as part of a fire-flow test for calibration (see Case Study in Section 7.7).

4.2.1.3 Chlorine Decay Tests

Chlorine bulk reaction and wall reaction (or demand) testing procedures can be used to determine the reaction parameters used in water quality models. Bottle tests measure the rate of chlorine reaction that occurs in the bulk flow independent of wall effects. This procedure is performed by first measuring the chlorine at a representative location such as in the effluent from a water treatment plant. Then several bottles are filled with the same water and kept at a constant temperature. Separate bottles are subsequently opened at intervals of several hours (or days) and the chlorine content is measured. The resulting record of chlorine at different times is used to estimate the bulk reaction rate. See AWWA (2004) for a more complete protocol for this test.

The purpose of the chlorine decay field testing procedure is to estimate the chlorine wall demand coefficient for representative pipes in the distribution system. The method described here involves the measurement of chlorine concentrations in a pipe segment under controlled flow conditions and use of the resulting chlorine measurements to determine the wall reaction rate for that pipe segment. The method is designed to be complementary with C-factor testing so that it can be conducted in conjunction with a C-factor test. The method is considered to be experimental and feasible only for pipes that are expected to have relatively high wall reaction values, such as smaller diameter unlined cast iron pipes. For the smaller diameter unlined cast iron pipes, pipe sections with a length in the range of 1,500 to 2,000 feet will be required to estimate wall demand. For other types of pipes that typically have low wall decay factors (e.g., plastic and new pipes), the required length of the pipe may be so long as to make this test impractical. Other factors that should be considered in selecting sites include the following:

- Ability to measure flow in the pipe.
- Ability to valve off the pipe segments.
- Presence of a reasonable chlorine residual (preferably > 0.4 mg/L) at the upstream end of the pipe segment.
- Ability to vary flow in the pipe over a reasonable flow range (e.g., for a 6” pipe, a range of flows of 100 to 500 gpm would be desirable).
- Ability to estimate the actual pipe diameter for the pipe segment.

For the selected pipe segment, major lateral(s) and downstream segments should be valved off to control flow in the pipe. Two or three sampling points should be established along the segment of interest (upstream, downstream, and an optional midpoint). Typically, these would be taps on fire hydrants. Prior to the testing, the taps should be run for several minutes to clean out the line. The approximate travel time through the pipe should be calculated and chlorine measurements taken from upstream to downstream so that approximately the same parcel of water is sampled at each station. Flow measurements can be made at any location within the segment.

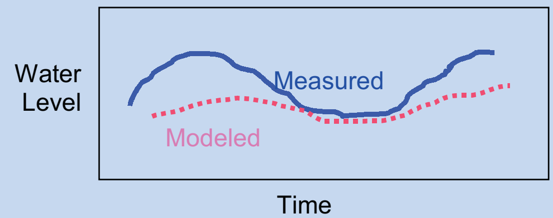
The test should be repeated for three flow values: a low flow rate, a medium flow rate, and a high flow rate. During each flow test, chlorine residual should be measured at each of the two or three sampling points. Since relatively small variations in chlorine concentration are expected, a good quality field chlorine meter should be employed and three replicates should be taken at each sampling point for each flow test. Following the field analysis, a spreadsheet can be used to back calculate the resulting wall reaction coefficients, or a water distribution model can be used to determine the wall reaction coefficient through trial and error.

4.2.2 Dynamic Calibration Methods

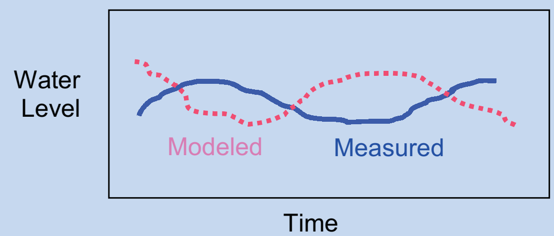
Dynamic calibration methods are associated with the use of an EPS model. The dynamic calibration methods include: (1) comparison of modeled results to measurements made in the field over time, and (2) tracer studies. In both cases, model parameters are adjusted so that the model adequately reproduces the observed behavior in the field. Tracer studies are discussed in detail in Chapter 3.

Comparison of modeled and measured data can be used for calibration of both hydraulic and water quality models. The most commonly measured hydraulic data are tank water levels, flows, and pressures. Frequently, this information is routinely reported through SCADA systems to a database and can be extracted. In other cases, continuous flow meters or pressure gages must be installed to collect data during a test period. Generally, tank water level data and flow measurements are the most useful form of data for calibrating an extended period model. Under average water use conditions, temporal variations in pressure measurements typically vary over a relatively small range and then only in response to variations in tank water levels. As a result, they are less useful in calibrating model parameters. If pressure measurements are going to be used for

If measured and modeled records of tank water levels do not agree well, the relationship between the two traces can provide clues as to the potential problems. In the example depicted below, the timing of the fill and draw cycles in the measured and modeled results are quite close but the modeled and measured depth of the fill cycles vary significantly. This suggests that the system demands may be in error, resulting in an incorrect amount of flow entering the tank.



In the second example illustrated below, the magnitude of the change in water level is quite close in the modeled and measured results, but the timing of the fill and draw cycles differ. This is typically caused by errors in the pumping controls in the model, resulting in pumps being turned on and off at the wrong time.



dynamic calibration, the system must be stressed by conducting fire-flow tests during the testing period. The primary model parameters that are adjusted during dynamic calibration are: demand patterns, pump schedules and pump curves, control valve settings, and the position (open or closed) of isolation valves.

Dynamic calibration procedures using tracer study data is discussed via a case study in Section 4.4 of this chapter. Dynamic calibration can also be used for calibrating water quality parameters, such as the wall demand coefficient for computing chlorine residuals. Generally, water quality field studies are performed in conjunction with field hydraulic studies or with a tracer study. For chlorine models, measurements of chlorine are taken at frequent intervals in the field at representative sites. These may include dedicated sampling taps, hydrants, tank inlet/outlets, or other accessible sites. Continuous chlorine meters may also be used. During the model calibration process, the model is first calibrated for hydraulic parameters, and water quality coefficients are subsequently adjusted so that the model results match the field data.

4.3 Manual Calibration and Automated Calibration

The aforementioned process of adjusting model parameters so that the model reproduces the hydraulic and/or water quality results measured in the field can involve a significant amount of effort in large or complex systems. As discussed earlier in this chapter, there are many parameters that can be adjusted in the model and the combinations of possible parameter values can sometimes appear to be quite overwhelming. Typically, a manual trial and error approach is used. The most influential parameters can be identified based on sensitivity analysis and then adjusted to see if they improve the results. This process is continued until an acceptable level of calibration is achieved or until budgetary constraints dictate closure. It is not unusual for many (dozens or even hundreds) separate model runs to be made in this process.

An extension to the manual calibration process is an automated approach that allows the computer to search through different combinations of model parameters (with a realm of realistic values) and to select the set of parameters that results in the best match between measured and modeled results. The development of this type of program has been the topic of many studies over the past 25 years (Walski et al., 2003).

Automated methods require a formal definition of an objective function for measuring how good a particular solution is. Generally, the value of a solution is measured by a statistic that reflects the deviation between measured and modeled results in flow and pressure. A commonly used objective function is minimization of the square root of the weighted summation of the squares of the differences between observed and predicted values. The weighting is used to establish a relationship between the errors associated with flow and pressure. For example, the user may choose a 1-psi error in pressure prediction to be equivalent in value to a 10-gpm error in flow.

In most automated methods, the user also groups pipes by common characteristics, such as age, material, and nodes, into common demand characteristics such as residential or commercial. The user then specifies a range of allowable values for pipe roughness factors or a range of multipliers applied to the existing roughness factors. Similarly, a range of allowable demand multipliers is also specified, as are potential pipes where an existing isolation valve may be closed. The optimization routine is then applied and the roughness, demands, and isolation valve positions are selected that result in the minimum error.

Though manual calibration still remains the predominant methodology, automated calibration methods are becoming more available in commercial modeling packages. It is likely that as the automated calibration methods are refined, the technology will expand for routine use with EPS hydraulic and water quality models.

4.4 Case Studies

In order to illustrate some of the calibration methods described earlier in this chapter, two case studies are presented in this subsection. The two case studies are similar in general methodology but differ in the overall scale and specifics of the study area. In both cases, the distribution system model that was used as a starting point for the calibration exercise was part of a skeletonized model extracted from unspecified portions of the GCWW distribution system.

Most larger urban water systems generally have at least a skeletonized model of their distribution system. It should be noted that (as discussed in Chapters 2 and 3 of this report) a skeletonized model denotes a model that includes only a major subset of actual pipes rather than all pipes in the distribution system. The extracted system model was modified and converted to EPANET format for use in this project. The modifications included: addition of key pipes, updates to consumer demand data, and an interconnection between the case study area and the full system by a fixed grade node (reservoir). These portions of the base model had been previously calibrated using various dynamic calibration methods and were used for routine water utility work. For the purposes of calibration, separate field studies were conducted in each study area.

In both field studies, a food-grade conservative tracer (calcium chloride) was introduced into the system and its movement through the system was monitored by both grab sampling and continuous monitoring (CM) stations installed at key locations in the distribution systems. The CM stations were installed at hydrants which were left partly open for the duration of the study to minimize travel time between the main and sampling location. Each open hydrant was added as a new demand node in the EPANET network model. Additionally, several ultrasonic flow meters were installed to provide continuous flow measurements at key locations. The general procedures, methodology, and instrumentation used in these field studies are consistent with those presented in Chapter 3.

4.4.1 Case 1 - Small-Suburban, Dead-End System

This system is part of a larger pressure zone. It was selected because of the relatively compact size and simple structure, fed by a single supply pipe with no additional storage. As a result, the movement of the tracer was relatively rapid through the system and it could be monitored with continuous meters placed at several locations. The general layout of this subsystem, the location of the injection site, and the monitoring locations for this study are shown in Figure 4-7.

The calcium chloride tracer was injected as two pulses, a two-hour pulse followed by a 2.5-hour period of no injection and then followed by a higher concentration pulse of two hours duration. The injection rate and the resulting concentration of the tracer in the distribution system just downstream of

Compliance with state and federal regulations during a tracer study is obviously quite important. In order to ensure that the tracer will not exceed allowable levels, it is necessary to monitor information such as the rate of injection of the tracer, the flow in the receiving pipe, and the resulting concentration in the receiving pipe. Frequently, a safety factor for the injection rate is included to account for uncertainty. In this field study, the tracer injection rate was very low and the flow meter on the injection pump provided approximate values. Chloride concentrations were monitored at a suitable location approximately 100 feet downstream of the injection point with a travel time of approximately 10 minutes. Due to unexpected variations in flow through the pipe, delay in measurements, and related computations (associated with tracer travel time), chloride values exceeding the target level were experienced for a brief period before the injection rate was adjusted.

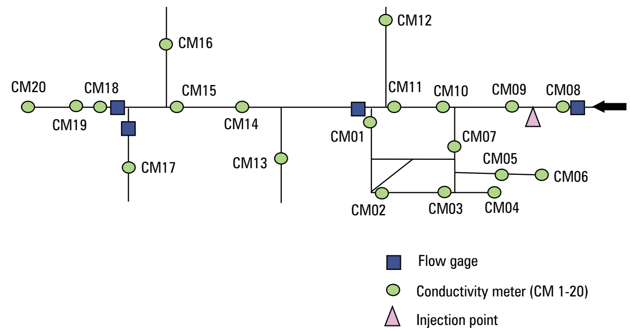


Figure 4-7. Schematic Representation of Small-Suburban Dead-End System.

the injection point were carefully monitored to ensure that the resulting chloride concentration did not exceed the secondary maximum contaminant level (MCL) of 250 mg/L for chloride.

The movements of the tracer pulses were monitored by using both manual sampling and continuous conductivity meters located throughout the distribution system. Additionally, four ultrasonic flow meters were installed in the study area to provide continuous flow measurements at key locations within the distribution system.

In preparation for the calibration process, the conductivity readings were converted to chloride concentrations using a relationship developed in the laboratory. Figure 4-8 shows the relationship between conductivity and chloride and the best-fit linear and polynomial relationships between them. This conversion was necessary because conductivity is not a truly linear parameter and, as a result, cannot be simulated exactly in a water distribution system model. The converted continuous concentration readings were then compared to the manually collected data for quality control purposes. Figure 4-9 shows the resulting chloride data set that was used at one location as a basis for evaluating model predictions as part of the calibration process.

The preliminary results indicated some discrepancy between the EPANET-model predicted values and the

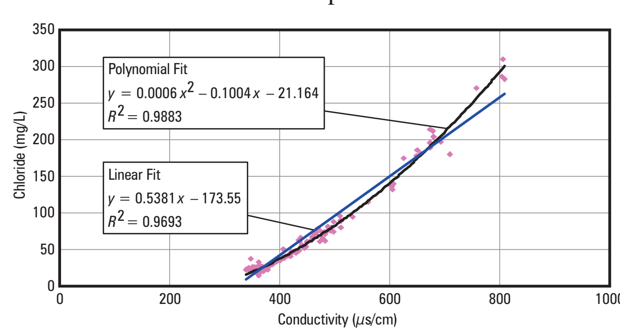


Figure 4-8. Empirical Relationship Between Chloride and Conductivity.

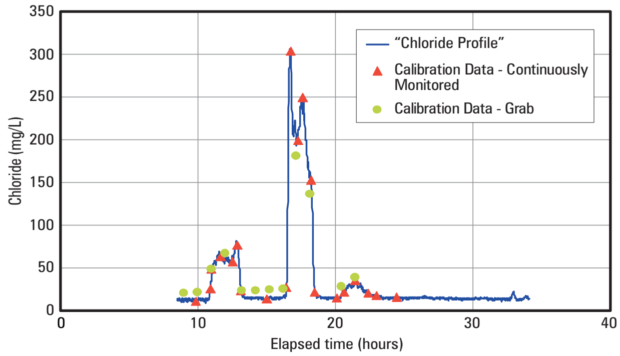


Figure 4-9. Sample Chloride Data Used at One Station for Calibration.

actual field-measured values, indicating the need for model refinement and re-calibration to improve the prediction capability of the EPANET model. Therefore, EPANET modeling was performed to evaluate the following four levels of model refinements:

- Level 1 (prior to calibration): A skeletonized EPANET model was used with the original hourly demand pattern provided by GCWW and a time-step injection pattern of 60 minutes.
- Level 2: The same as Level 1, but a refined 10-minute time-step pattern for injection was used along with the conversion of the original hourly demand patterns to 10-minute patterns.
- Level 3: The same as Level 2 with a refined demand pattern for each node using the field-measured flow data, addition of demand nodes representing water demand of the partially open hydrants, adjustment for a large industrial user of water in the study area (based on data obtained during the study), and the residential water billing information provided by GCWW.
- Level 4: The same as Level 3 with a detailed all-pipe (non-skeletonized) EPANET model.

The results of the four-stage model refinement and calibration process are shown in Figure 4-10 for a continuous monitoring location (CM-18) located on the main feeder pipe. As illustrated, the improvements in the demand estimates and inclusion of the system details in the all-pipe model resulted in a vast improvement in the model's prediction ability for that monitoring location. Similar results were found for most monitoring locations on the main pipe.

During the calibration and refinement process, various model inputs such as flow, demand, and pipe characteristics were adjusted to improve the model prediction. The EPANET model was considered to be calibrated for the area when the field data matched the model-predicted output to an acceptable degree based on visual observation. Depending upon the location of the junction (where the model predictions are compared with the field values), both concentration and predicted time of tracer arrival might not be in perfect agreement due to local variation in demands, local flow velocities, and dilution impacts. The sharp tracer fronts observed in this field study made it difficult to employ quantitative statistical measures (e.g., mean error, standard deviation, root mean square error). Therefore, a graphical (visual) approach was considered to be more suitable for model calibration

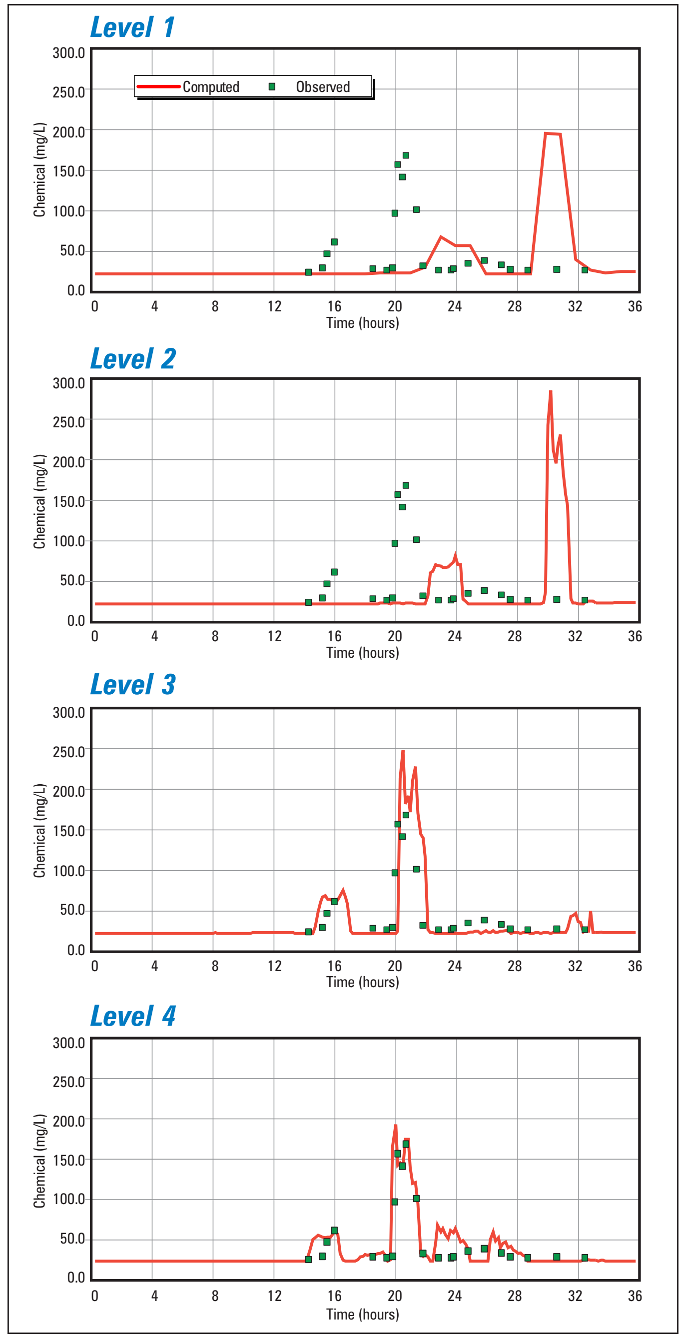


Figure 4-10. Comparison of Model Versus Field Results for Continuous Monitor Location CM-18 at Various Calibration Stages.

in this application. For example, if the prediction of the arrival time for the tracer differs by even a few minutes from the observed arrival time, use of these standard measures of error could result in a high number, even though the prediction could be viewed graphically as very good.

The calibration of the "looped" portion (referring to the portion of the network on the bottom right hand side of Figure 4-7) of this network proved to be more difficult and the results for some monitoring locations on the looped piping were less satisfactory. The most problematic were continuous monitoring locations CM-02 and CM-04. Monitoring station CM-02 was located near the confluence of two separate loops, with the actual monitored connection being slightly offset from the junction node. Examination of the model results showed that flow reached that junction from both directions and small variations in the amount of flow in each of the loops resulted in very different travel times. As illustrated in Figure 4-11, this complex travel pattern along with the offset location of the monitoring station resulted in poor

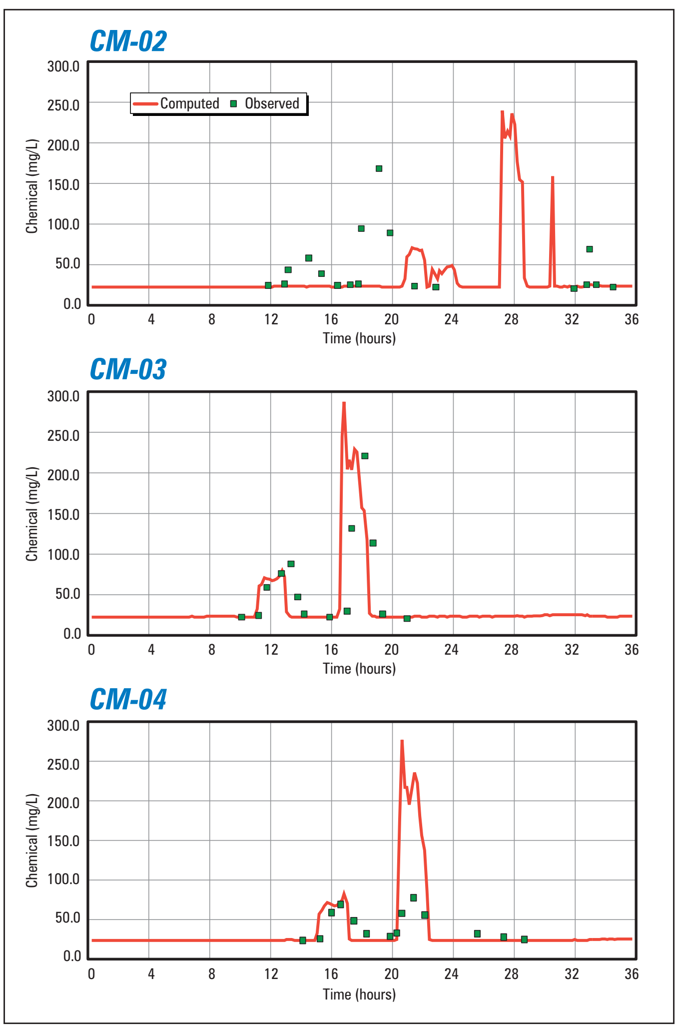


Figure 4-11. Calibration of "Looped Portion."

prediction of travel time to that station. Also, monitoring station CM-04 is located at the end of a dead-end pipe section and travel to this node is strongly influenced by demands at the very far end of the dead-end section. As illustrated in Figure 4-11, this resulted in a poor match of the peak concentration during the second pulse. It is also postulated that dispersion, which is not represented in EPANET, may have had an influence on the peak concentration due to the very low velocities in the dead end pipe. In some cases, this could also be caused by inaccurate C-factors as applied to the distribution system. However (as illustrated in Figure 4-11), for monitoring location CM-03 located in the main part of the looping system, the model and field agreement was quite good.

Case 1 data illustrates that, depending upon the level of refinement and calibration, there is a significant variation in the capability of a model to accurately represent the system. In general, the parts of the network that are configured as trees (main stem with branches) are more easily calibrated by making adjustments in demands. For looping parts of the system and at dead-ends, results are very sensitive to small variations in demands and system configuration, leading to the possibility of significant prediction errors at some locations. Uncertainty in demand estimates can be a major source of error in the model estimates.

4.4.2 Case 2 - Large-Suburban Pressure Zone

Similar to Case 1, a field study and calibration exercise was carried out in a large-suburban, pressure zone. This area was selected in order to demonstrate the application of tracer studies and calibration techniques in a more complex area. The selected area contained multiple pumps and tanks. The selected distribution system area is representative of relatively complex, well-gridded systems found in many larger water systems. The layout of the system, the location of the injection site, and the monitoring locations are shown in Figure 4-12.

Two separate tracer studies were performed in this zone. The first study was used to further calibrate the skeletonized model received from the water utility. The second study served as a validation event to test the veracity of the calibrated model. In the calibration event, the tracer was introduced directly into the main feed line servicing the entire area (characterized by higher flow/higher pressure). In the validation study, the tracer was pulsed. A total of 34 continuous conductivity meters were installed in the system. Four flow meters were temporarily installed to provide flow measurements at key locations.

During the calibration study, the calcium chloride tracer was injected into the main feed line serving the

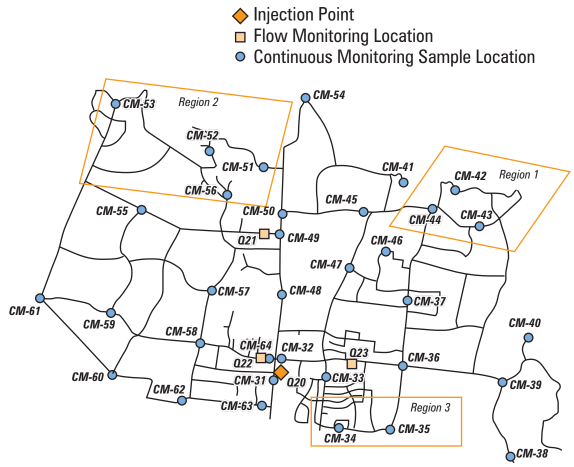


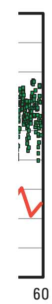
Figure 4-12. Schematic Representation of Case 2 Study Location.

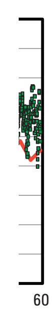
area for a period of 6 hours. In the validation study, the tracer was pulsed by fill and draw cycles in a storage tank at the same location. In both cases, a target chloride concentration of 190 mg/L or lower was set in order to safely not exceed the 250 mg/L secondary MCL for chloride.

During the calibration process, initial EPANET model simulations were reviewed in detail to determine the flow patterns around various monitoring locations and to attempt to identify causes for discrepancies in the observed and predicted values. A careful examination of the areas of significant discrepancies indicated that these were primarily limited to three geographic sub-regions within the skeletonized network. In addition to these three sub-regions, there were a few isolated locations where the predicted tracer pattern did not match the observed tracer pattern from the field study. The modeling team carefully examined each of these regions and addressed the zonal issues accordingly. The three sub-regions are shown in Figure 4-12.

In Region 1 (CM42, CM43, and CM44), the field data indicated that the tracer arrived at these continuous monitoring locations several hours before the model's prediction. On closer inspection, it was found that a potential flow path existed which was not included in the skeletonized model. While the pipe diameter was small, it significantly altered the hydraulic water flow path to that region. This missing pipe-link was added to the model, using the appropriate pipe parameters. Furthermore, the modeling team investigated the GIS database to see if there were any substantial changes in these areas since the time when the original water demand patterns were developed five years ago. The updated GIS information indicated a presence of recent housing development in that region. Therefore, additional demand nodes were entered into the EPANET model to accommodate for this development. Another possibility for the discrepancy was that the demand in this region was significantly higher than the average residential demand modeled in the area. To simulate this possibility, a sensitivity analysis was performed in which the modeled demand in this region was doubled. The model-predicted results improved significantly for this region based on these three adjustments.

In Region 2 (CM52, CM53, CM55 and CM56), an opposite phenomenon to that in Region 1 was observed. The field data indicated that the tracer arrived several hours after the model's prediction. One possible explanation was that this region had lower demand than the average residential demand modeled in this area. The flow meter data upstream of this location supported this theory as the EPANET predicted flow in this pipe was much higher than the field observed flow (see Figure 4-13a). To simulate this possibility, the local demand in this region was reduced by 30 percent in the model. The resultant flow matched the flow meter data (see Figure 4-13b). Also, similar to Region 1, it was found that a potential flow path had again been left out due to skeletonization of the model, which affected CM52. This pipe link was added to the model using the appropriate pipe parameters. Distribution mains between CM55 and CM53 were also found to have been upgraded since the EPANET network model was





developed for this area. The EPANET model pipes for this location were updated using the newer information. The model-predicted results improved significantly for this region based on these three adjustments.

In Region 3 (CM34 and CM35), the field data indicated that the tracer arrived at locations CM34 and CM35 several hours after the model's predicted arrival time. However, the field-verified tracer arrival time matched the predicted tracer arrival time at location CM33 which is slightly upstream of these locations. Also, a review of the water flow pattern in this region indicated that the water traveled from CM33 towards CM34 and CM35 (at all times). Based on the demands in the EPANET model, the pipe lengths, and the regional water flow information, the delay in tracer arrival at CM34 and CM35 could not be explained. A closer inspection of the region revealed a complex grid of interconnected pipes in this region, which were skeletonized as two parallel pipes. This skeletonization eliminated a number of different possible hydraulic flow paths between CM 33 and CM34/CM35. Also, in the EPANET model inputs, it appeared that the demand close to CM34 and CM35 was set artificially higher (to account for the overall demand in the skeletonization process). This model setup resulted in the predicted faster tracer arrival times at CM34/CM35 than those observed in the field. To account for this anomaly, a few pipe segments from the master plan were added to the skeletonized model of this region to better simulate the actual grid demands near CM34 and CM35. This model adjustment resulted in better prediction of the tracer arrival times.

During the calibration process, as demands were adjusted, a mass balance was performed for each hour to ensure that the net water demand in the study area remained the same, i.e., the increase in the demand at certain nodes was balanced by the reduced demand at other nodes to eliminate any net impact on water demand. In the final refinements, a multiplier of 2.0 was used for the base demand in Region 1, and a multiplier of 0.7 for the base demand in Region 2. These refinements showed some improvement in the model's ability to correctly predict the tracer arrival time and concentration. These calibration efforts resulted in a relatively well-calibrated network model. However, some local problems remained, especially in looped areas and areas that were branched off from the main lines.

The substantial changes made to the EPANET skeletonized model representing the large area necessitated a validation process. Therefore, the calibrated EPANET model input file from the first event was used to validate the model's capability to predict the results during the subsequent tracer addition. For the purposes of this validation, the data

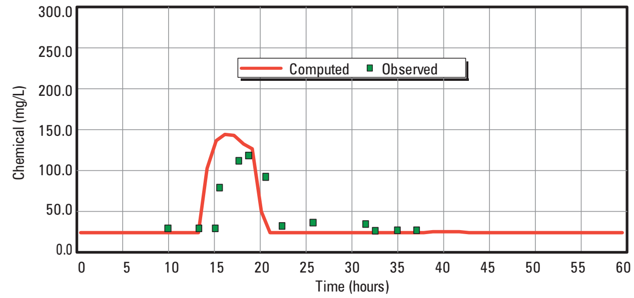


Figure 4-14a. Chloride Concentration for Calibration Event at Continuous Monitor Location CM-59.

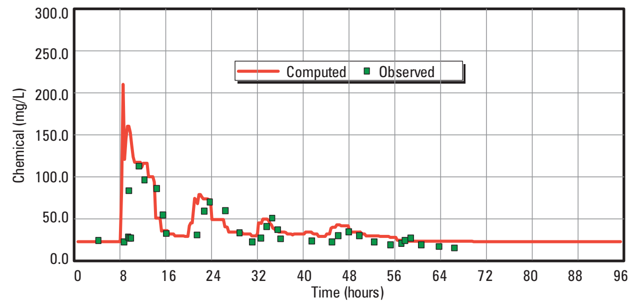


Figure 4-14b. Chloride Concentration for Validation Event at Continuous Monitor Location CM-59.

from the second set of pulsed injections was modeled using the calibrated EPANET network model for the study area to see how the predicted results compared with the continuous monitoring data collected during this event. The modeled and measured concentrations are compared in Figure 4-14a for the EPANET calibration. A similar comparison is shown in Figure 4-14b for the validation study.

Additionally for the purposes of this analysis, the EPANET predictions from the validation event were compared with the field results for each monitoring site and each site was given a grade as follows:

- Very good match (within ±20 percent of the actual concentration and within ±1 hour of the actual tracer arrival time)
- Moderate match (within ±30 percent of the actual concentration and within ±5 hours of the actual tracer arrival time)
- Poor match (greater than ±30 percent of the actual concentration or greater than ±5 hours of the actual tracer arrival time).

Of the 34 monitoring sites in this study area for the validation event, 15 received a grade of very good match, 14 were in the moderate match category, and 5 received the lowest grade of poor match. In general, it was found that better matches occurred on larger pipes serving large populations, while the poorest matches occurred in more localized loops serving fewer customers. These results are, in general, quite similar to the results obtained for the calibration event, and most problems repeatedly occurred at the same locations for both events. The validation event results confirm the fact that the calibrated EPANET network model can now be used to predict the outcome of a separate event to the same degree of accuracy.

4.5 Future of Model Calibration

Calibration continues to be a major focus of most modeling efforts. It can provide a model that may be used with greater confidence and produce results that are commensurate with the important decisions that are made based on the application of the model. However, there is significant room for improvements in calibration methodologies and in developing a standardized set of calibration protocols. This has led to an active research program in this area that is expected to continue into the future.

4.5.1 Calibration Standards

The following issues are raised frequently in the field of distribution system modeling:

- extent of calibration needed for various applications, and
- standards for calibration.

Though these are very reasonable questions, straight forward answers are usually not readily available.

There is general agreement in the modeling profession that the amount and degree of calibration required for a model should depend upon the intended use of the model (Engineering Computer Applications Committee [ECAC], 1999). Some applications such as design and water quality analysis typically require a high degree of calibration, while other uses, such as master planning, can be performed with a model that has not been calibrated to such a high standard. However, there are no universally accepted standards.

In the United Kingdom, there are performance criteria for modeling distribution systems (Water Authorities Association and WRc, 1989). These are expressed in terms of the ability to reproduce field-measured flows and pressures within the model, as shown below.

Flow

1. ±5 percent of measured flow when flows are more than ±10 percent of total demand (transmission lines).
2. ±10 percent of measured flow when flows are less than ±10 percent of total demand (distribution lines).

Pressure

1. 0.5 m (1.6 ft) or 5 percent of head loss for 85 percent of test measurements.
2. 0.75 m (2.31 ft) or 7.5 percent of head loss for 95 percent of test measurements.
3. 2 m (6.2 ft) or 15 percent of head loss for 100 percent of test measurements.

In 1999, the AWWA Engineering Computer Applications Committee developed and published a set of draft criteria for modeling. These were not intended as true calibration standards, but rather as a starting point for discussion on modeling needs. These criteria are summarized in the following table (Table 4-2).

Table 4-2. Draft Calibration Criteria for Modeling (based on ECAC, 1999)

Intended Use	Level of Detail	Type of Simulation	Number of Pressure Readings[1]	Accuracy of Pressure Readings	Number of Flow Readings	Accuracy of Flow Readings
Long-Range Planning	Low	Steady-State or EPS	10% of Nodes	±5 psi for 100% Readings	1% of Pipes	± 10%
Design	Moderate to High	Steady-State or EPS	5% - 2% of Nodes	±2 psi for 90% Readings	3% of Pipes	± 5%
Operations	Low to High	Steady-State or EPS	10% - 2% of Nodes	±2 psi for 90% Readings	2% of Pipes	± 5%
Water Quality	High	EPS	2% of Nodes	±3 psi for 70% Readings	5% of Pipes	± 2%

[1] The number of pressure readings is related to the level of detail as illustrated in the table below.

Level of Detail	Number of Pressure Readings
Low	10% of Nodes
Moderate	5% of Nodes
High	2% of Nodes

At this point, there is no clear movement toward establishing calibration standards. However, it is likely that the need for further guidance in this area will increase as the extent and sophistication of modeling continues to expand.

4.5.2 Technological Advances

Research is continuing in two areas that strongly influence the likelihood of improved calibration of water distribution systems models: monitoring technology and optimization techniques. The available optimization techniques (and those under development) have been briefly discussed in this chapter and in Chapter 2. Active research and development areas include optimization techniques for water quality calibration, EPS models, and use of tracer data. Areas of research, development, and experimental applications in monitoring technology include less expensive meters that can be inserted into pipes in the distribution system and automated monitoring for use in conjunction with tracer studies (as discussed in Chapter 3).

4.6 Summary and Conclusions

Water distribution system models can be used for a number of purposes. Many of these uses result in engineering decisions that involve significant investments. It is therefore important that the model represent the "real world." Calibration techniques can be used to ensure that the mathematical representation of the system, or model, adequately simulates the system.

Calibrating a model is a difficult task because there are many parameters that can be adjusted and finding the combination of parameters that result in the best agreement between measured and modeled results is often challenging. It is recommended that the model be calibrated using one set or more of field data and subsequently validated with an independent set of field data.

Calibration of water distribution system models can be viewed in many dimensions. Hydraulic calibration is used to adjust the parameters associated with hydraulic simulations, while water quality calibration is applied to reaction rates and other parameters that control the water quality simulation. Static or steady-state calibration methods are used with steady-state models and data collected at instantaneous snapshots in time, while dynamic calibration is conducted with extended-period simulation models and time-series data. Manual calibration techniques involve manual application of models in a trial-and-error mode, while automated calibration uses the power of the computer to search a wide range of solutions and to select the set of parameters that best achieve a stated objective. Automated methods can reduce much of the tedium associated with calibration but require the modeler to formally define a quantitative objective function for measuring how well the model matches the field data. Such automated methods are becoming more available in commercial modeling packages.

> During the calibration process, it is important to eliminate various sources of errors in modeling. As a first pass, a modeler should check for typographical errors, accuracy of affected piping layout and material, general system flow, velocity values, and distribution system demands. Thereafter, one should look into other sources of errors such as skeletonization, valve position, geometric node placement anomalies, SCADA data errors, and pump performance.

Two case studies are presented in this chapter. The case studies differ in terms of the overall scale of the study area. In both cases, the distribution system model that was used as a starting point for the calibration exercise was part of a skeletonized model. The results demonstrate the need for adequate model calibration.

The extent of calibration and calibration techniques are a major issue in most modeling efforts. There is significant potential for improvements in calibration methodologies and in standardization of calibration. This has led to an active and continuing research program in this important area.

References

AWWA. *Computer Modeling of Water Distribution Systems (M32).* AWWA, Denver, CO. 2004.

ECAC. "Calibration Guidelines for Water Distribution System Modeling." Proceedings, AWWA ImTech Conference, New Orleans, LA. April 18-21, 1999.

McEnroe, B.M., D.V. Chase, and W.W. Sharp. "Field Testing Water Mains to Determine Carrying Capacity." Miscellaneous Paper EL-89, U.S. Army Engineer Waterways Experiment Station. Vicksburg, MS. 1989.

Vasconcelos, J.J., L.A. Rossman, W.M. Grayman, P.F. Boulos, and R.M. Clark. *Characterization and Modeling of Chlorine Decay in Distribution Systems.* AWWA and AwwaRF, Denver, CO. 1996.

Walski, T. M, D.V. Chase, D.A. Savic, W.M. Grayman, S. Beckwith, and E. Koelle. *Advanced Water Distribution Modeling and Management.* Haestad Press, Waterbury, CT. pp 268-278. 2003.

Water Authorities Association and WRc. *Network Analysis – A Code of Practice.* WRc, Swindon, UK. 1989.

Williams, G.S., and A. Hazen. *Hydraulic Tables.* John Wiley & Sons, NY. 1920.