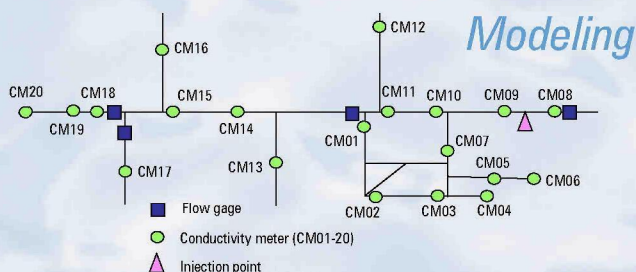


Water Distribution System Analysis: Field Studies, Modeling and Management

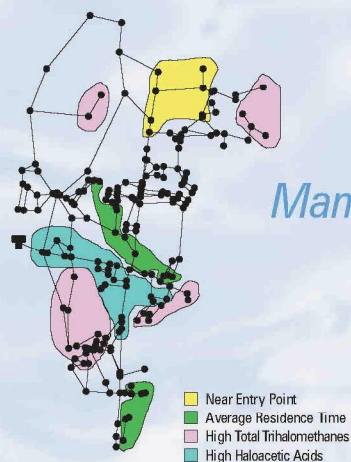
A Reference Guide for Utilities



Field Studies



Modeling



Management

**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



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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

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Acronyms and Abbreviations

AC	Alternating Current	DWQM	Dynamic Water Quality Model
ACCNSCM	Arsenic and Clarifications to Compliance and New Source Contaminant Monitoring	EBMUD	East Bay Municipal Utility District
ADAPT	Areal Design and Planning Tool	EDM	Electronic Distance Measurement
ADEQ	Arizona Department of Environmental Quality	EMPACT	Environmental Monitoring for Public Access and Community Tracking
Al ₂ (SO ₄) ₃	Aluminum Sulfate	EOSAT	Earth Observation Satellite
AM/FM	Automated Mapping (or Asset Management)/Facilities Management	EPA	U.S. Environmental Protection Agency
AMR	Automated Meter Reading	EPS	Extended Period Simulation
ASCE	American Society of Civil Engineers	ESSA	Environmental Science Services Administration
ATSDR	Agency for Toxic Substances and Disease Registry	EWS	Environmental Warning System
AWWA	American Water Works Association	FC	Fecal Coliform
AwwaRF	Awwa Research Foundation	FeCl ₃	Ferric Chloride
C	Coefficient of Roughness	FOH	Federal Occupational Health
ClO ₄	Perchlorate Anion	GA	Genetic Algorithm
CaCl ₂	Calcium Chloride	gal	Gallon
CAD	Computer-Aided Design	GBF	Geographic Base File
CADD	Computer-Aided Design and Drafting	GC	Gas Chromatograph
CDC	Centers for Disease Control and Prevention	GCWW	Greater Cincinnati Water Works
CFD	Computational Fluid Dynamics	GIS	Geographic Information System
CIS	Customer Information System	GPD	Gallons Per Day
CM	Continuous Monitoring	gpm	Gallons Per Minute
COGO	Coordinated Geometry	GPS	Global Positioning System
CRT	Cathode Ray Tube	GRASS	Geographic Resources Analysis Support System
CWS	Contamination Warning System	GUI	Graphical User Interface
DBP	Disinfection By-Products	GWR	Ground Water Rule
DBPR1	Disinfectant By-Product Rule - Stage 1	HAA	Haloacetic Acid
DBPR2	Disinfectant By-Product Rule - Stage 2	HAA5	The five Haloacetic Acids
DC	Direct Current	HACCP	Hazard Analysis Critical Control Point
D.C.	District of Columbia	HGL	Hydraulic Grade Line
DEM	Digital Elevation Model	HSPP	Health and Safety Project Plan
DIME	Dual Independent Map Encoding	ICR	Information Collection Rule
DLG	Digital Line Graph	IDSE	Initial Distribution System Evaluation
DSOP	Distribution System Water Quality Optimization Plan	IESWTR	Interim Enhanced Surface Water Treatment Rule
DSS	Distribution System Simulator	ILSI	International Life Sciences Institute
DTM	Digital Terrain Model	I/O	Input/Output
		ISE	Ion Selective Electrode
		ISO	Insurance Services Office
		LCR	Lead and Copper Rule

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

A Reference Guide for Utilities

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.

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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

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.

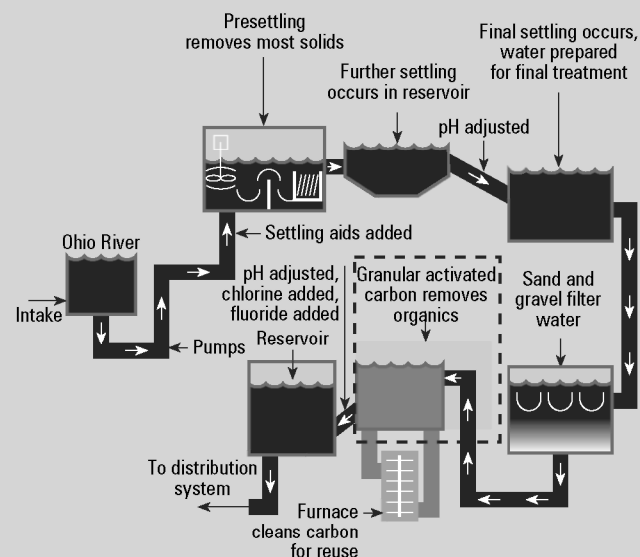


Figure 1-1. Water Treatment Process at the Miller Plant on the Ohio River (Adapted from: GCWW 2005).

utilities to support public safety, protect public health, and promote economic growth (Clark and Feige, 1993).

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

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.

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).

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.

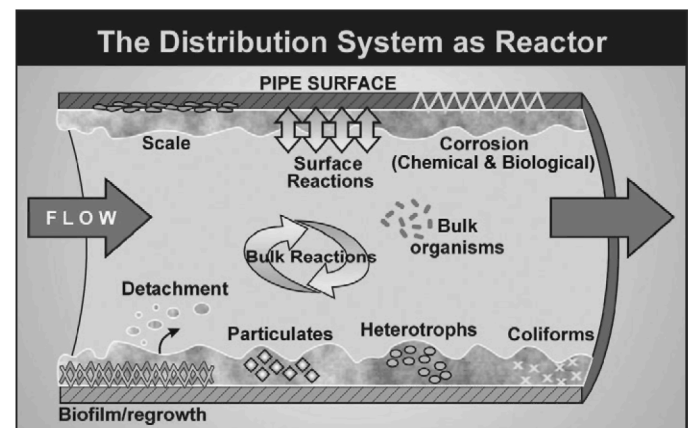


Figure 1-2. Distribution System Interactions that Affect Water Quality (Adapted from: MSU, 2005).

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

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.

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

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 breaches 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

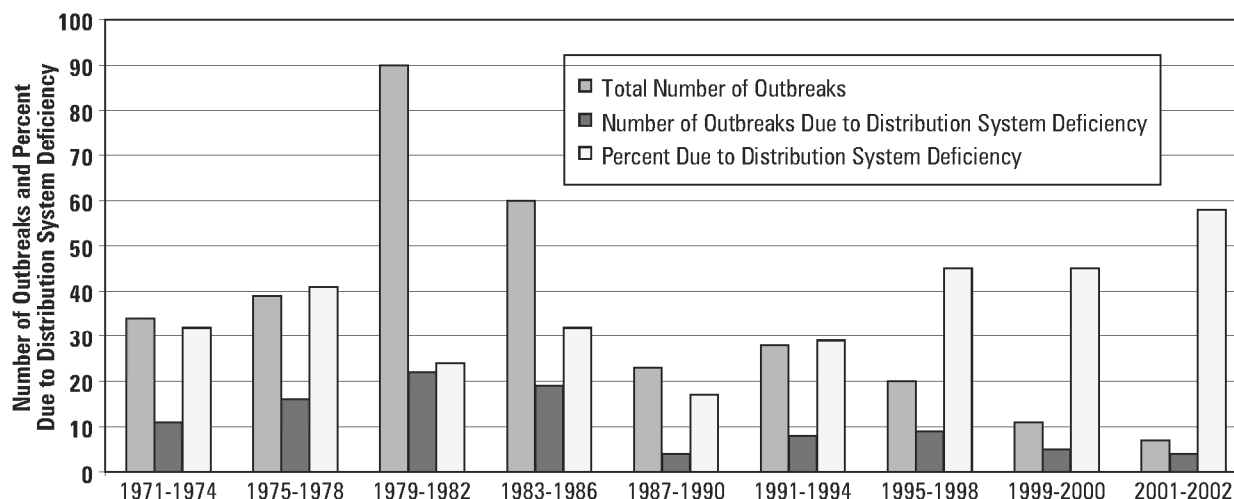


Figure 1-3. Total Number and Proportion of U.S. Waterborne Diseases Associated with Water Distribution System Deficiencies.

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 in 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

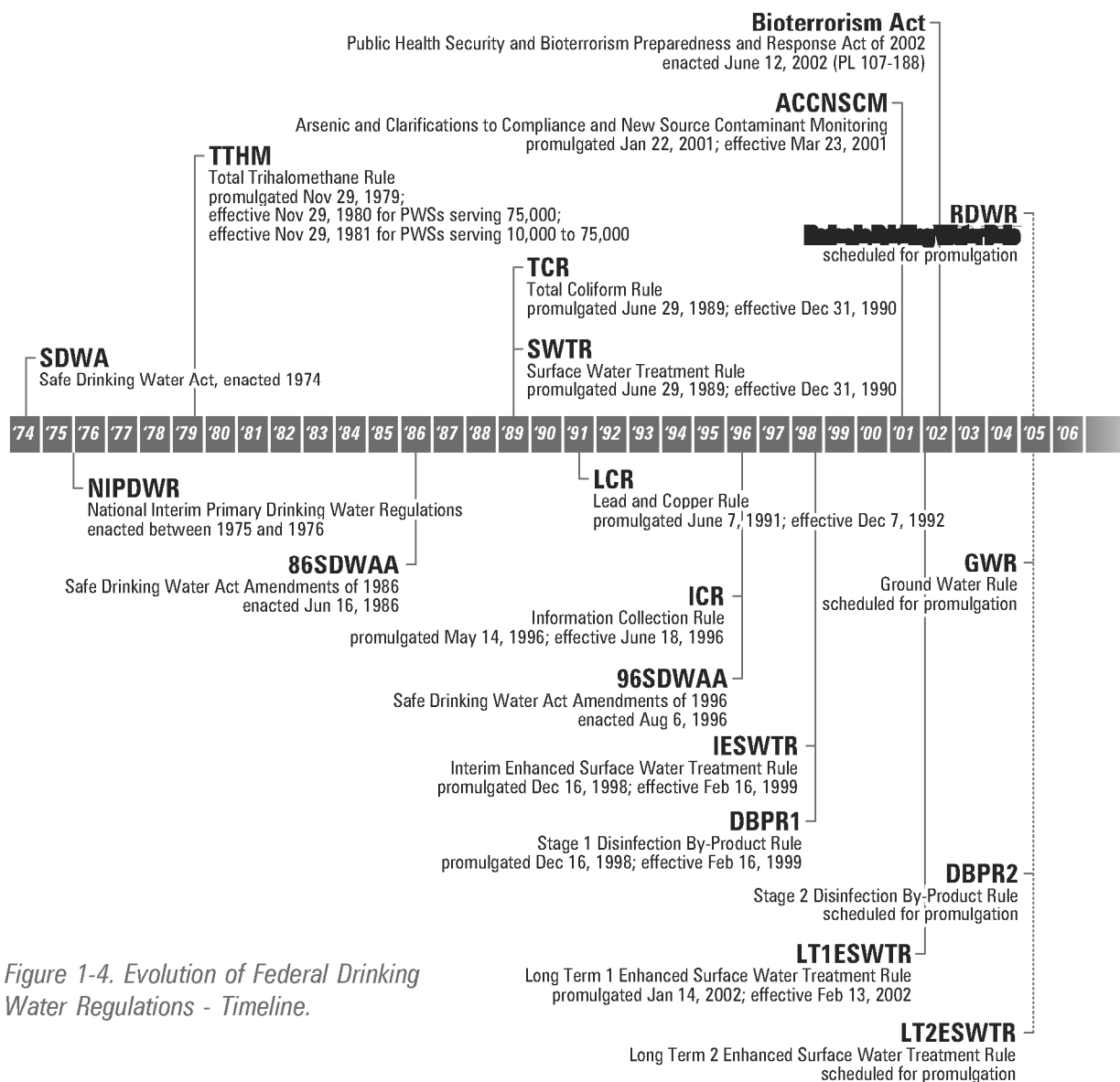


Figure 1-4. Evolution of Federal Drinking Water Regulations - Timeline.

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 <i>Cryptosporidium</i> , 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 <i>Cryptosporidium</i> , 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 chlorine 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. Boulous, 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.

conomic 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.

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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,

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.

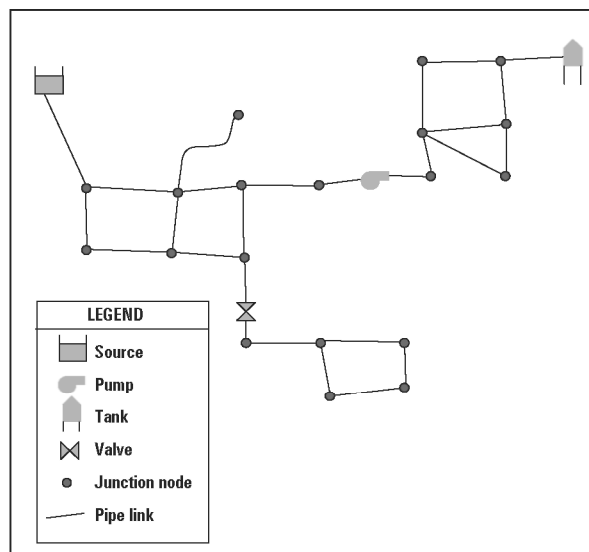


Figure 2-1. Simple Link-Node Representation of a Water Distribution System.

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

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/ft² (N/m²)

γ = fluid (water) specific weight, in lb/ft³ (N/m³)

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

g = acceleration due to gravity, in ft/sec² (m/sec²)

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 ft³/sec (m³/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.

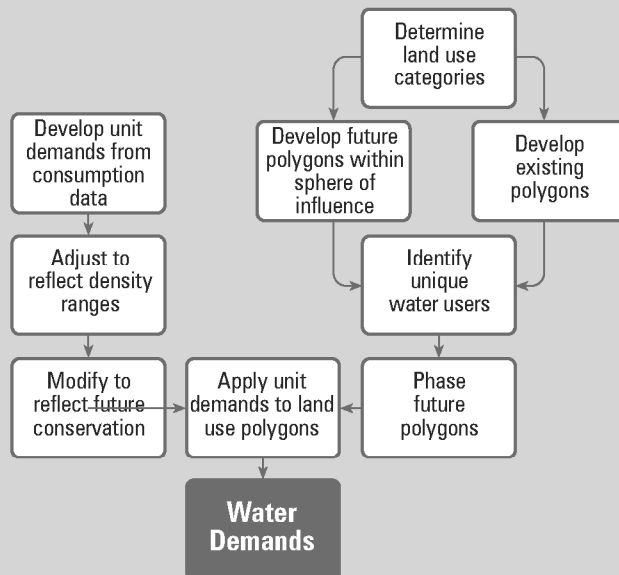


Figure 2-2. A Flow Chart for Estimating Future Water Demand Based on Land-Use Methodology.

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

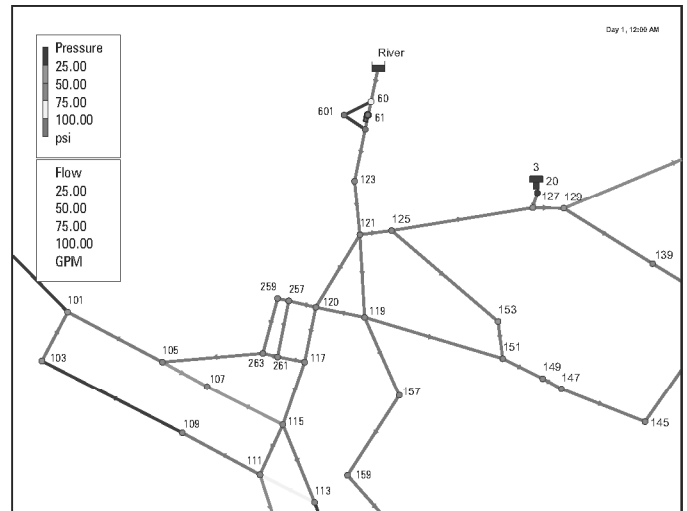


Figure 2-3. EPANET Graphical Output Showing Flow and Pressure.

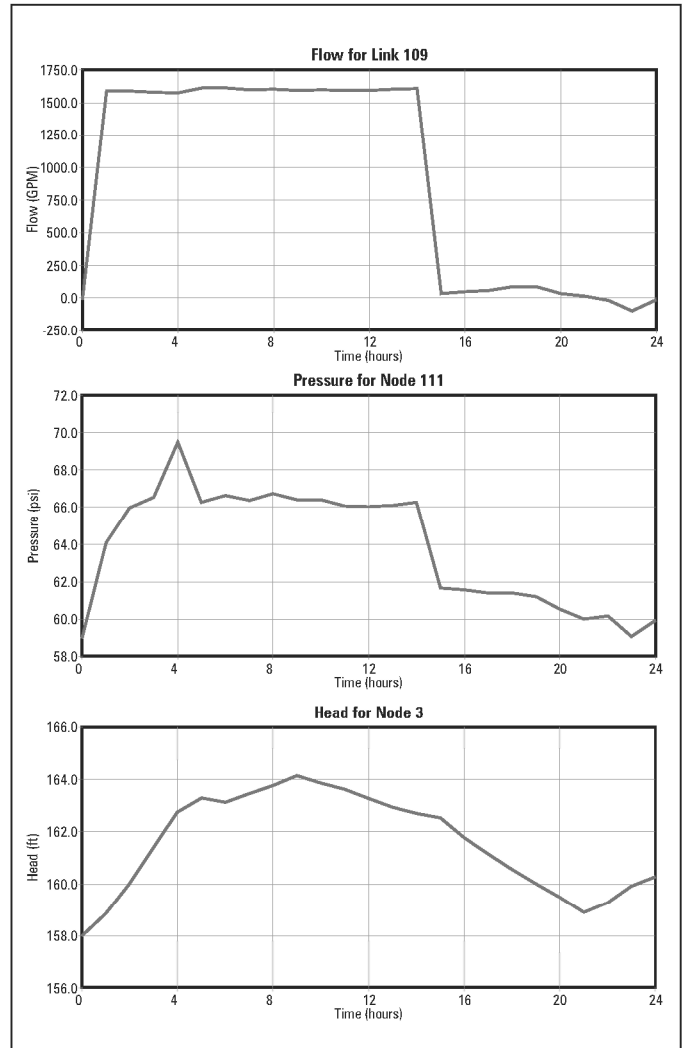


Figure 2-4. Sample EPANET Time Series Plots of Flow, Pressure, and Tank Water Level.

The figure consists of two screenshots of the EPANET 2 software interface. The top screenshot displays the 'Node Properties' table, and the bottom screenshot displays the 'Link Properties' table. Both tables are part of a larger window titled 'EPANET 2 - Net3.net - [Netwo...]'.

Node Properties Table:

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

Link Properties Table:

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

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

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

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.

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

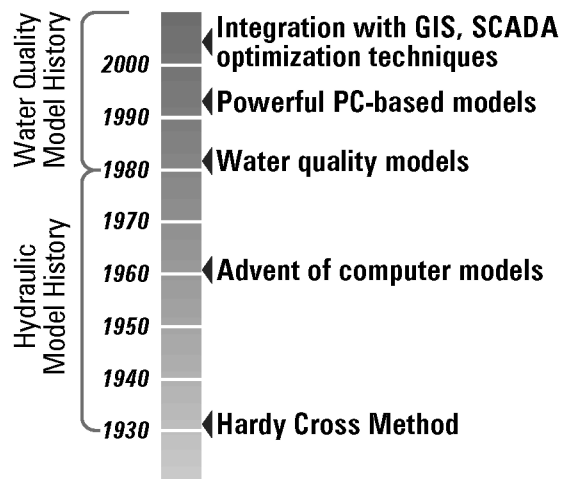


Figure 2-6. Illustration of the Evolution of Hydraulic and Water Quality Models.

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:

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

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:

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

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 oxidizable 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:

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

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

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_{si} = flow from node s to i , 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_{ij} = decay coefficient 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

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.

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.

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/pipelinenetb.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.

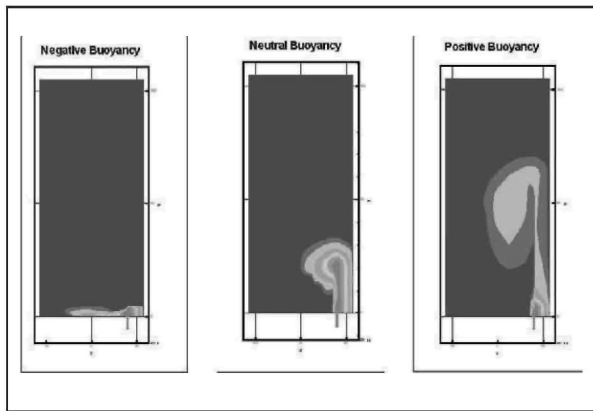


Figure 2-7. Graphical Output from a CFD Model Showing Tracer Concentration in a Tank.

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.

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.

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

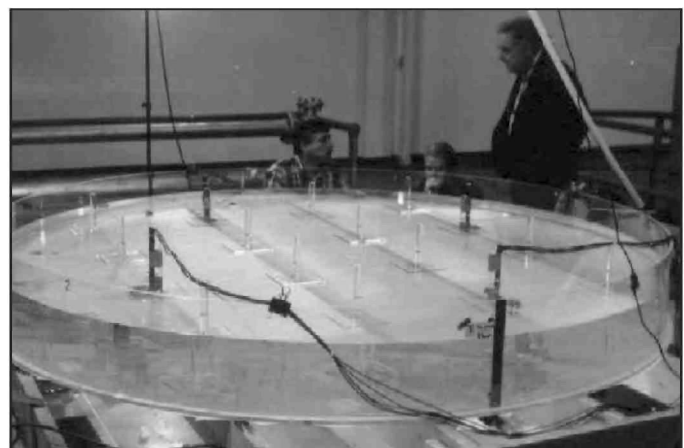


Figure 2-8. A Large Physical Model of a Tank (Source: Bureau of Reclamation Laboratory).

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.

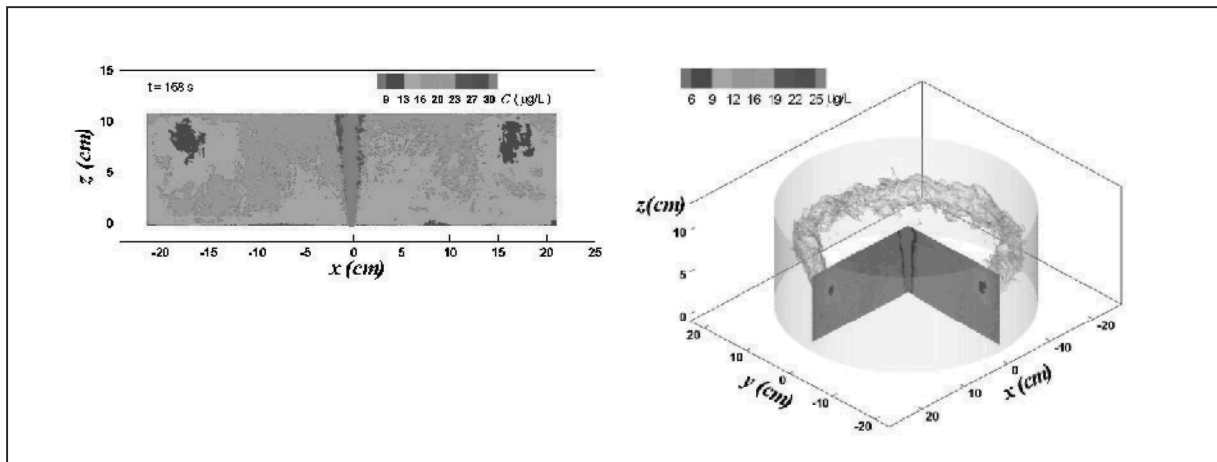


Figure 2-9. Graphical Output Based on 3-D Laser Induced Fluorescence with a Physical Scale Model Showing Mixing in Tank (Source: Georgia Tech).

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.

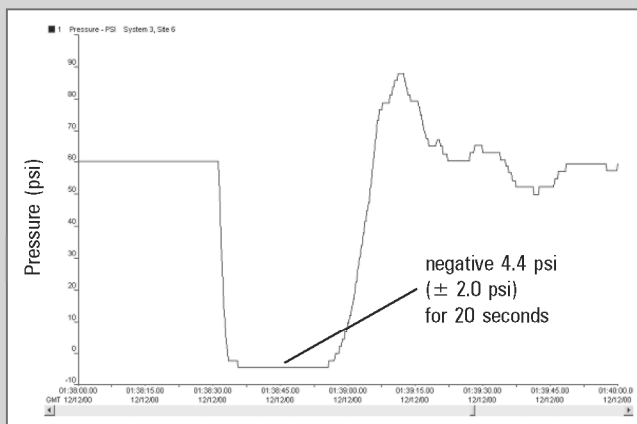


Figure 2-10. Negative Pressure Transient Associated with a Power Outage.

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).

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.

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

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.

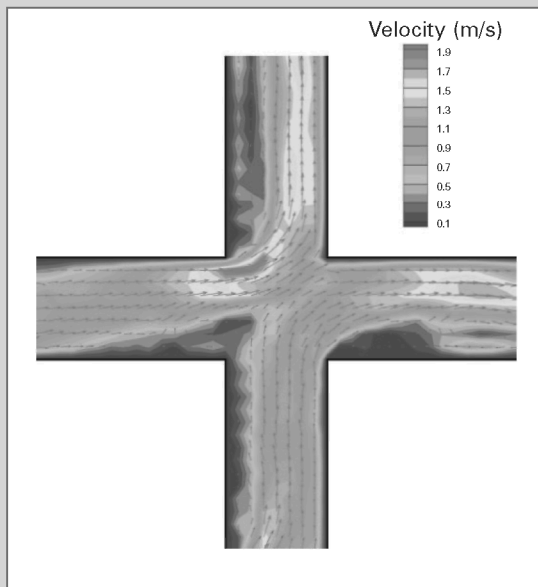


Figure 2-11a. Velocity Field at a Junction.

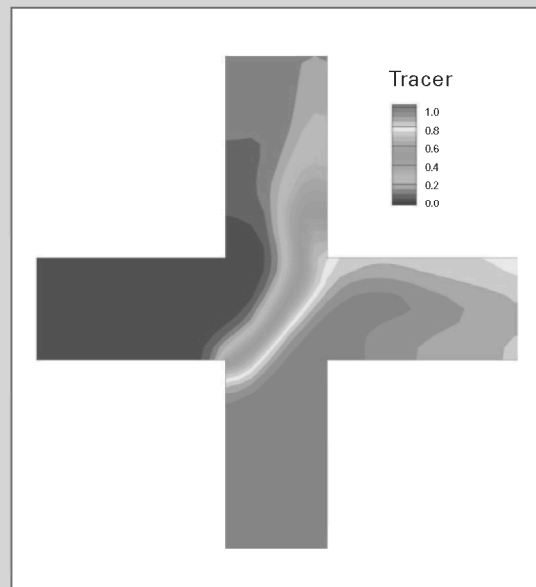


Figure 2-11b. Tracer Concentration at a Junction.

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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 time-line (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 et 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

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.

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.

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

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).

levels. EPA reports that taste thresholds for sodium vary significantly among individuals, ranging from 30 to 460 mg/L (EPA, 2003b).

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 [$\text{Al}_2(\text{SO}_4)_3$]. 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 ₂ SiF ₆ NaF Na ₂ SiF 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 ₂ SiF 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.lciltld.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 ₂ SiF ₆	hydrofluosilicic acid
KCl	potassium chloride
LiCl	lithium chloride
NaF	sodium fluoride
Na ₂ SiF 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.

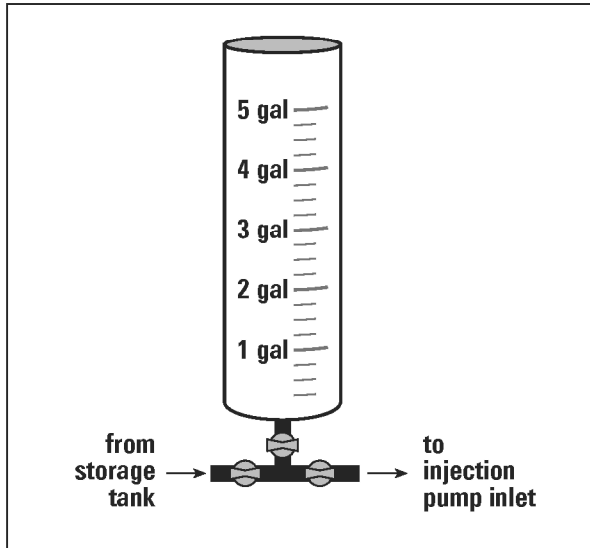


Figure 3-1. Flow Calibration Tube.

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

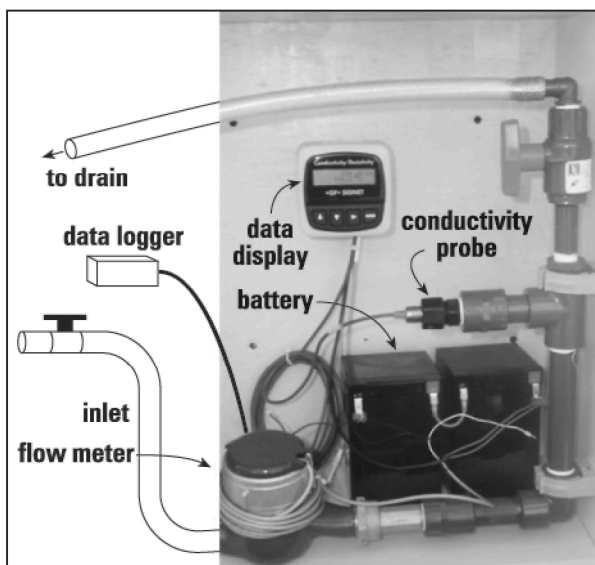


Figure 3-2. Automated Monitoring Station.

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).

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.

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 inquiries at the study site. This same statement should be used by utility personnel to answer any telephone inquiries 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.

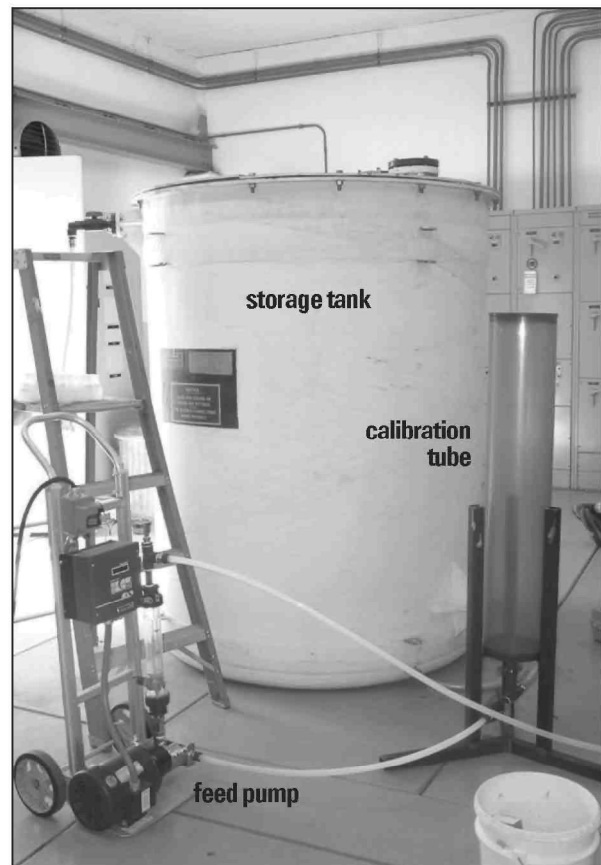


Figure 3-3. Tracer Injection Setup (Storage Tank, Calibration Tube and Feed Pump).

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 recirculated 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, L³/T

Q_U = flow upstream of injection point, L³/T

Q_T = flow of tracer solution, L³/T

C_D = concentration of tracer material downstream of injection point, M/L³

C_B = background concentration of tracer material in distributed water, M/L³

C_T = tracer concentration, M/L³

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 at 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.

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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.

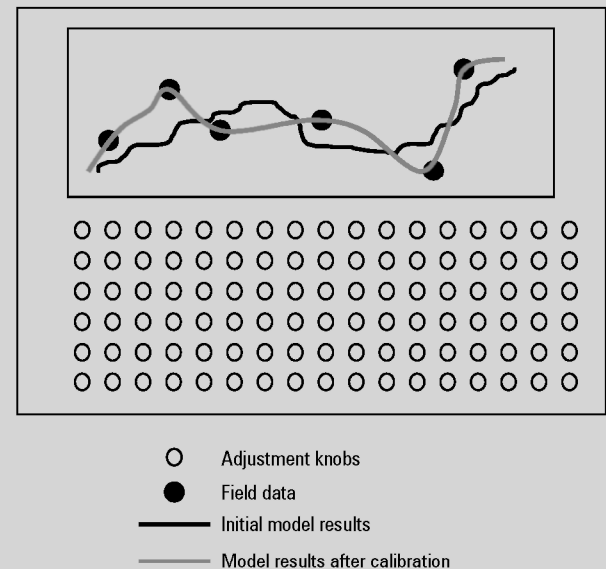


Figure 4-1. Conceptual Representation of Calibration.

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 initially 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.

- **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.

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

- **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.

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.

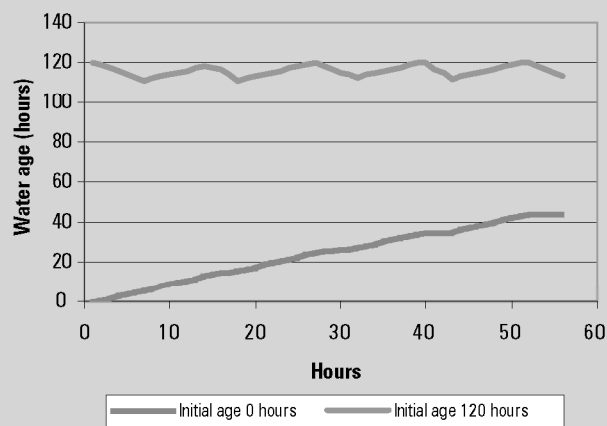


Figure 4-2. Effects of the Initial Water Age on the Modeled Results.

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

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.

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

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

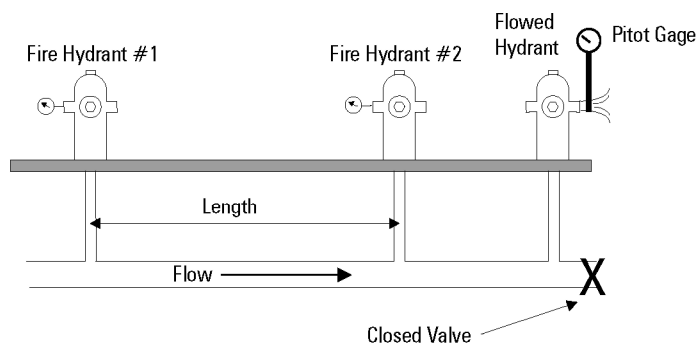


Figure 4-3. Schematic of Standard Two-Gage C-Factor Test Setup.

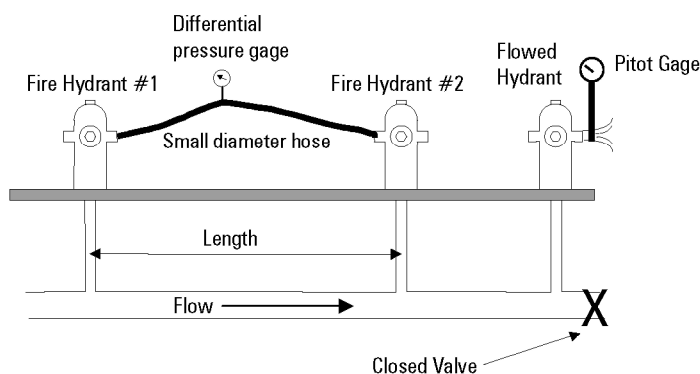


Figure 4-4. Schematic of Parallel Hose C-Factor Test Setup.

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

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.

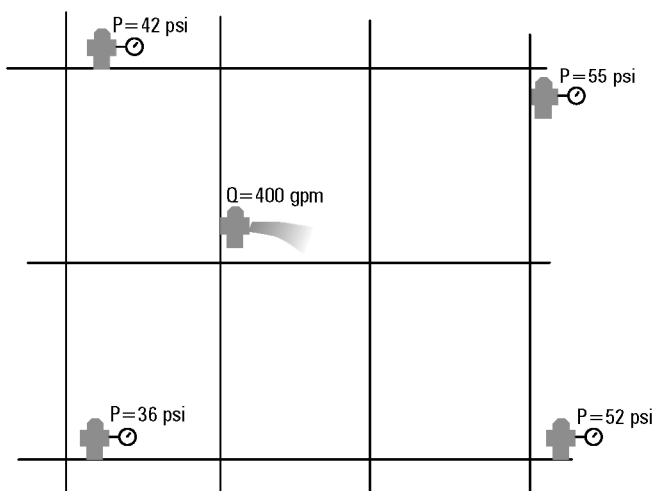


Figure 4-5. Fire-Flow Test Setup.



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.

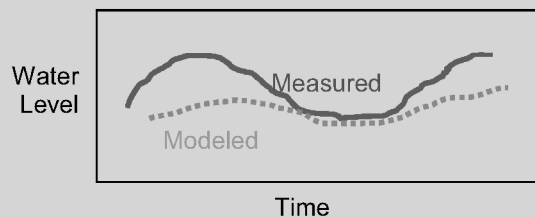
For the selected pipe segment, major lateral(s) and downstream segments should be valved off to control flow in the pipe. Two or three sampling points should be established along the segment of interest (upstream, downstream, and an optional midpoint). Typically, these would be taps on fire hydrants. 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.

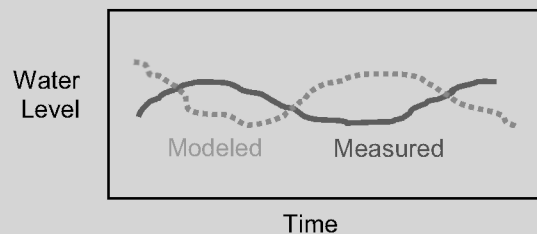
4.2.2 Dynamic Calibration Methods

Dynamic calibration methods are associated with the use of an EPS model. The dynamic calibration methods include: (1) comparison of modeled results

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.



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

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 sub-system, 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.

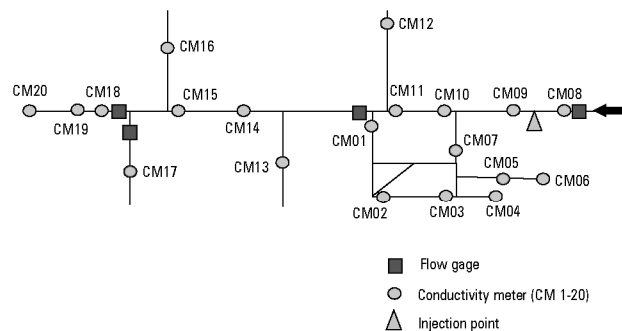


Figure 4-7. Schematic Representation of Small-Suburban Dead-End System.

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

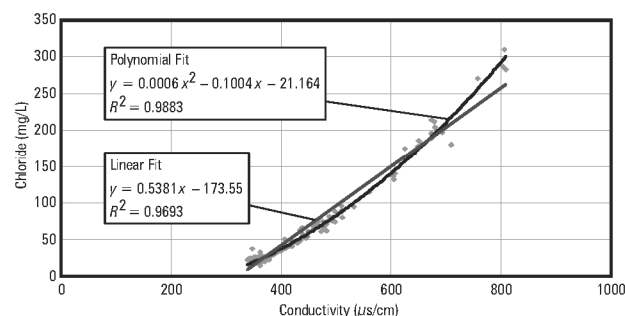


Figure 4-8. Empirical Relationship Between Chloride and Conductivity.

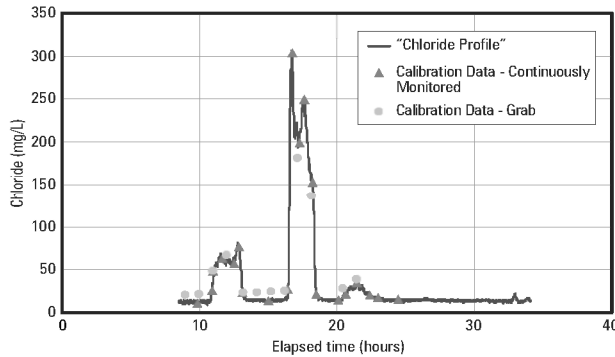


Figure 4-9. Sample Chloride Data Used at One Station for Calibration.

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

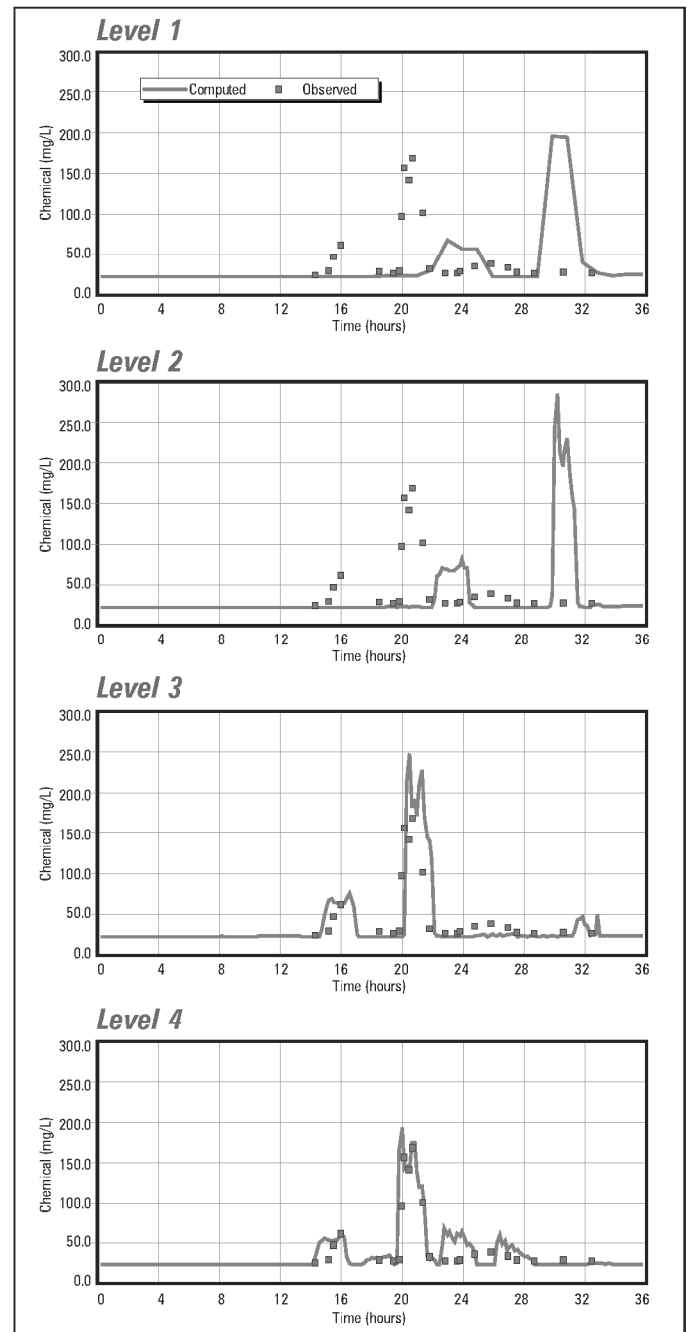


Figure 4-10. Comparison of Model Versus Field Results for Continuous Monitor Location CM-18 at Various Calibration Stages.

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

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

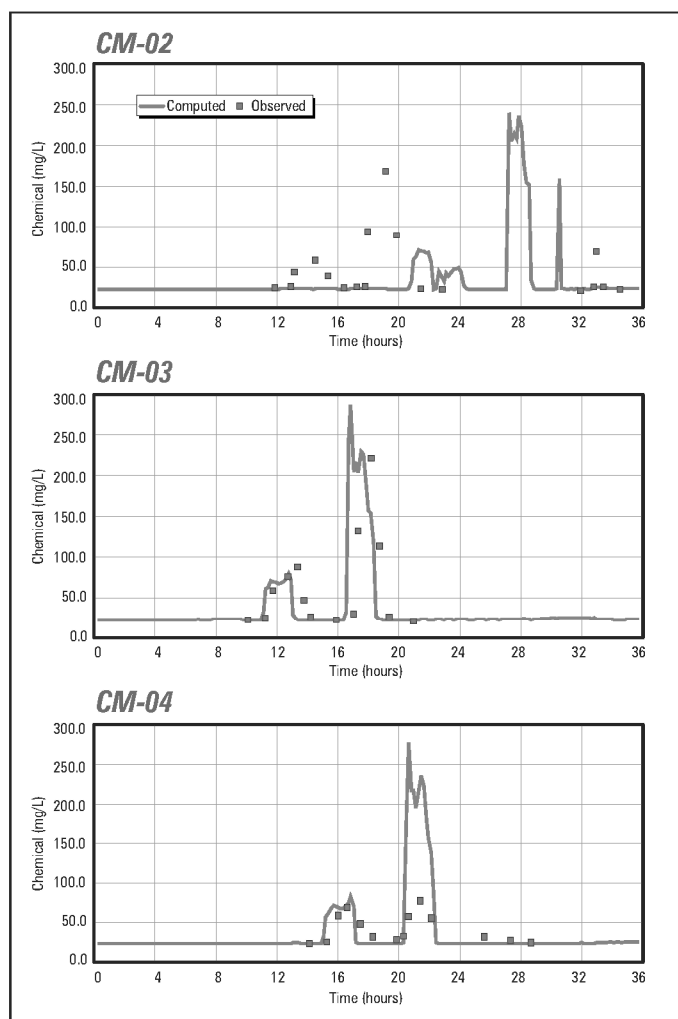


Figure 4-11. Calibration of “Looped Portion.”

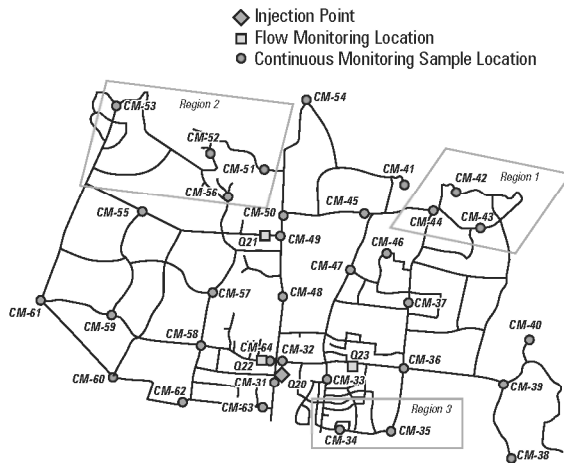


Figure 4-12. Schematic Representation of Case 2 Study Location.

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 CM33 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

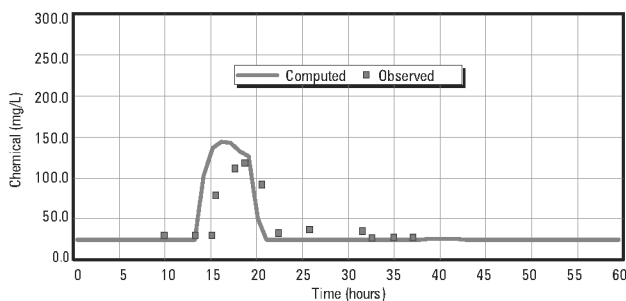


Figure 4-14a. Chloride Concentration for Calibration Event at Continuous Monitor Location CM-59.

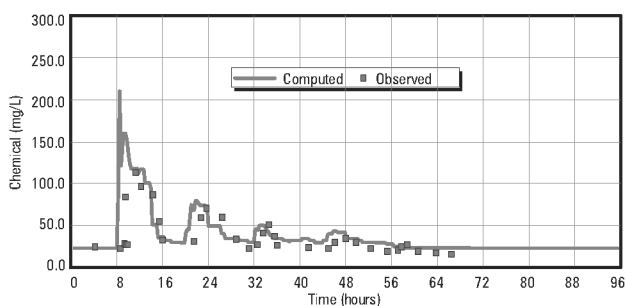


Figure 4-14b. Chloride Concentration for Validation Event at Continuous Monitor Location CM-59.

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	$\pm 10\%$
Design	Moderate to High	Steady-State or EPS	5% - 2% of Nodes	± 2 psi for 90% Readings	3% of Pipes	$\pm 5\%$
Operations	Low to High	Steady-State or EPS	10% - 2% of Nodes	± 2 psi for 90% Readings	2% of Pipes	$\pm 5\%$
Water Quality	High	EPS	2% of Nodes	± 3 psi for 70% Readings	5% of Pipes	$\pm 2\%$

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

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.

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.

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.

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Chapter 5

Monitoring Distribution System Water Quality

Monitoring a water supply system and its various components facilitates the gathering of data about the state of the system (physical, operational and water quality). If the state of the system has minimal changes in time or space, a simple monitoring system may be sufficient to define and manage the system characteristics. However, if there is potential for significant variation in the state of the system, the monitoring system must be adequately designed to capture that variability. Thereafter, depending upon the type and magnitude of variability, an appropriate response can be provided to restore the “normal” system state. This chapter will focus on monitoring water quality-related parameters in a distribution system.

In a distribution system, water quality may vary due to factors such as normal patterns in water consumption, seasonal variations, source water quality, components of the distribution system, operation of the system, retention time in storage, travel time in the piping system, or the condition of the system itself. Variability may also result from unusual occurrences, such as intentional/accidental intrusions of contaminants, or chemical processes such as nitrification. Design of a water quality monitoring program must take into account both the nature of the variability and the manner in which monitoring data will be used. In other words, the objective of the monitoring program must be defined along with appropriate output or reporting requirements.

In general, monitoring systems can be defined based on the uses or needs of the monitoring program, the general type of monitoring to be performed (manual grab sampling and/or continuous automated online monitoring), or the specific monitoring equipment characteristics. It is important to first establish a clear objective(s) for monitoring. Thereafter, depending upon the availability of funding, need, and expertise, one should select the appropriate sampling technique(s) and monitoring equipment. Once an appropriate monitoring system has been selected and implemented, it is important to operate and maintain the program to achieve optimal results and benefits. However, the system should be flexible enough so that it can be modified in case it does not meet the original objective(s).

This chapter discusses the various drivers or objectives for monitoring followed by a summary of available monitoring techniques. An overview of monitoring equipment is presented followed by guidelines for establishing monitoring requirements

(e.g., selection of parameters, number and locations of monitors, and monitor characteristics). Some guidance for engineering and evaluating remote monitoring systems is also presented, along with some EPA-sponsored monitoring case studies. The chapter concludes with a summary and a listing of references.

The recent studies involving the use of online continuous monitoring systems have resulted in large streams of data that document the minute-by-minute changes in water quality that exist at various points in the water networks. The application of this technology has the potential for providing new insights as to how water distribution systems may be operated and designed to improve water quality. However, these systems will require a relatively high level of sophistication in terms of data management, including the capability to generate real-time reports, graphical and visual representation of information, and compliance reports for meeting drinking water standards. Some of these data streams may well reveal excursions in water quality that constitute violations of current or future drinking water standards, or a security-related incident. This type of information may put pressure on drinking water utilities and regulatory agencies to take remedial action, possibly on an emergency basis, even when such actions may not be fully justified (or warranted). However, careful planning and negotiations with appropriate regulatory authorities to define these potential “excursions” and the proper corrective action to be taken would prevent any misunderstandings and minimize or eliminate the potential for unjustified enforcement or response actions.

5.1 Establishing Monitoring Objective(s)

In order to define and implement an effective monitoring plan, clear objectives must be established. Collecting data just for the sake of accumulating information is not cost effective. In drinking water systems, there are several specific reasons to collect data and, typically, the monitoring system is tailored to meet one or more of these needs. The objectives of monitoring distribution systems can be broadly classified into the following five uses:

- regulatory driven monitoring,
- security related monitoring,
- process control related monitoring,

Table 5-1. Federal Distribution System Water Quality Monitoring Requirements

Regulation	Monitoring Requirement(s)
TCR	Samples must be collected at sites that are representative of the water quality throughout the distribution system based on a site plan that is subject to review by the primacy regulatory agency. The minimum number of samples that must be collected per month depends on the population served by the system. For each positive total coliform sample, there are repeat sampling requirements, additional analyses, and an increased number of routine samples.
SWTR and IESWTR	Disinfectant residuals must be measured at TCR monitoring sites.
LCR	All systems serving a population > 50,000 people must do water quality parameter (WQP) monitoring. The number of sample sites for Pb/Cu and WQP monitoring is based on system size.
DBPR2	The IDSE requirement of DBPR2 in turn requires the establishment of a Standard Monitoring Program (SMP). The SMP will require one year of data on THMs and Haloacetic Acids (HAAs). The number of sampling locations is based on utility size and source characteristics. Modeling can reduce sampling requirements.

- water quality characterization (e.g., general, baseline, or other research-related monitoring), and
- multi-purpose (a combination of above) use of monitoring data.

The following subsections present the overall scope of each of these five objectives.

5.1.1 Regulatory Driven Monitoring

Various federal, state, or other governmental agencies have regulations that specify distribution system monitoring requirements. An overall review of federal regulations impacting distribution systems was presented in Chapter 1. The specific federal distribution system monitoring requirements (existing and proposed) are summarized in Table 5-1. In some cases, states have imposed more stringent criteria and monitoring requirements.

5.1.2 Security Related Monitoring

Assessments performed by utilities and various research studies have identified that water distribution systems are vulnerable to intentional (or accidental) contamination. In addition to “hardening” systems in order to deter intentional contamination, monitoring as part of an early warning system (EWS) has emerged as a logical approach to cope with potential contamination events. There are no existing or proposed standards for such monitoring. However, it is well recognized that monitors will need to be sufficiently sensitive to a broad range of potential contaminants and appropriately located to detect a contamination event within a reasonable time. Additionally, as detailed in EPA’s Response Protocol

Toolbox (EPA, 2003-2004), monitors must be an integral part of an emergency response management plan in order to be effective. Extensive research and development is underway on monitor development, calibration, and placement in response to the perceived security monitoring needs.

Currently, EPA has an ongoing test program to evaluate the potential of sensors monitoring routine online water quality parameters, such as pH, oxidation reduction potential (ORP), free chlorine, total organic carbon (TOC), conductivity, and turbidity, to serve as rapid detection devices for detecting contamination events in distribution systems. Online monitors were selected because response time is critical for achieving the objective of providing early warning. Both bench- and pilot-scale studies are being conducted at the Water Awareness Technology Evaluation Research and Security (WATERS) Center within the EPA’s Test and Evaluation (T&E) Facility in Cincinnati, Ohio. The bench-scale runs are designed to identify the detection threshold of each sensor for specific contaminants. The pilot-scale runs are designed to evaluate overall response of the selected sensors by injecting known quantities of potential contaminants into the distribution system simulator (DSS). For this purpose, several pilot-scale DSSs have been fabricated and used for these test runs. The sensor data are collected continuously and archived electronically to establish stable baseline conditions and to also record sensor responses to injected contaminants. Grab samples are collected periodically before and after injection of contaminants to confirm the sensor results.

5.1.3 Process Control-Related Monitoring

Monitors can also be used in a distribution system to provide real-time or near real-time information on water quality that can then be used to control treatment processes at a treatment plant or in the distribution system. The use of continuous chlorine monitors in the distribution system to control disinfectant feed rates at the plant or at in-distribution system booster chlorination stations are examples of this type of monitoring (Uber et al., 2003).

5.1.4 Water Quality Characterization

Information from long-term monitoring of distribution systems can be used to develop baseline trends in water quality for that system. Such information is useful in evaluating a water supply system and for planning upgrades or modifications to system design or operation.

Additionally, if this information is appropriately distributed, it builds consumer confidence and helps to keep customers up to date about the water quality so that they can use this information to make decisions about protecting their health. Currently, there are no standards or guidelines for this type of monitoring. However, for this information to be useful and cost-effective, a regular program for examining and analyzing the collected information is essential.

5.1.5 Multi-Purpose Use of Monitoring Data

Monitoring can be an expensive undertaking in terms of capital costs, as well as operation and maintenance (O&M) costs, including labor. Costs include the purchase and upkeep of equipment, laboratory analysis, labor, and consumable supplies. The investment in monitoring and automated monitoring systems is justifiable if the resulting data are used for more than one objective. For example, if data collected for security purposes can also be used for process control, it should be easy to justify potentially large investments in automated monitoring equipment. Monitoring systems should be properly designed in order to meet multi-purpose requirements.

5.2 Monitoring Techniques

The two major factors in designing and implementing an effective monitoring program are sampling techniques and equipment selection. This section focuses on available monitoring techniques. Samples can be collected and analyzed in two ways: grab samples and/or by automated online monitoring. Automated monitors (continuous or discrete) are sometimes supplemented with automated samplers that can collect both discrete and composite water samples for further analysis at a later date/time. Grab samples are collected manually and analyzed in the field or in the laboratory. Grab samples are labor-intensive in comparison to automated sampling and

provide snapshot information about the system at the time of sample collection. Automated monitoring uses online instrumentation, and data is collected by means of sensors and automated data loggers. They can also be tied to a SCADA System. High-end monitors require a higher capital expense for the purchase and maintenance of sensors, data acquisition, data communication, data storage, and data-processing hardware and software. However, this type of monitoring provides a continuous time-series profile of changes in water quality. Both automated and grab sampling can be incorporated into a comprehensive monitoring plan. These techniques are further discussed in the following subsections.

5.2.1 Manual Grab Sampling

Historically, routine water quality monitoring in distribution systems has been carried out through manual grab samples followed by analysis in the field or in the laboratory. Essentially, all regulatory monitoring is still carried out by this method. For example, samples required for large community water supply systems under the SWTR are manually

The equipment routinely required in a manual grab sampling program includes field sampling equipment (e.g., chlorine meter), safety equipment (vests, rain gear, and flashlights), and laboratory equipment. Consumable supplies include sampling containers, reagents, and marking pens. One should identify the needs and availability of equipment and supplies and investigate various sources for equipment. Because equipment malfunction or loss is possible, some redundancy in equipment is appropriate. Some important functions to consider when establishing a field sampling program include the following:

- Establish a systematic and organized method for all sampling and data recording. Take notes to document all aspects of the process.
- Provide training to sampling crews and specify these training requirements in the sampling program plan.
- Contingency planning is important; therefore, consider the potential for equipment malfunction, illness of crew members, communication problems, severe weather, malfunction, and customer complaints.
- Establish a communications protocol to coordinate actions. A means of communication is needed to respond to unexpected events. Alternatives include radios, cellular phones, walkie-talkies, or a coordinator in a vehicle to circulate among field crews.
- Calibrate field analytical equipment before and during the sampling activity.

collected at sites within the distribution system and tested for disinfectant levels in the field. Samples taken to satisfy the requirements of the TCR are also manually collected in the field and subsequently analyzed in the laboratory. Manual sampling is labor-intensive and the number of samples that can be collected is limited by availability of personnel and analysis costs. However, they are specified by some regulations. Potentially important events that may occur between the routine grab samples may be lost (e.g., process upset). Also, there is a potential for dismissing unusual grab sampling results as some type of manual monitoring error (Hargesheimer et al., 2002).

5.2.2 Automated/Online Monitoring

As stated in the report, "Online Monitoring for Drinking Water Utilities" (Hargesheimer et al., 2002), "There is an evolution from grab-sample monitoring to online monitoring as sampling, analysis, data processing, and control functions become more automated." Online monitoring requires a mechanism for moving the sample water from the distribution system to an instrument, appropriate instrumentation for analyzing the water, a mechanism for communicating the results, and a means of assessing the results of the monitoring. Additionally, the instrumentation must be periodically calibrated and maintained for quality control/quality assurance.

In the past, distribution system online monitors were typically housed in a controlled environment with sample lines from the distribution system to the instrument. This resulted in most instrumentation being located at facilities such as tanks and pump stations. The instrumentation was sometimes connected to a SCADA system so that results could be communicated to a central office. More recently, some instrumentation is available that is designed for installation in manholes or for direct insertion into water mains.

The American Society of Civil Engineers (ASCE), in concert with other leading organizations, entered into a cooperative agreement with the EPA to develop standards documents and guidance aimed at enhancing the physical security of the nation's water and wastewater/stormwater systems. Under this agreement, ASCE is leading the effort to develop guidelines for designing an online contaminant monitoring system (OCMS). The Interim Voluntary Guidelines for Designing an OCMS were published in December 2004 (ASCE, 2004). This document provides comprehensive information on several topics, including rationale for OCMS and system design basics, selection and siting of instruments, data analysis, and use of distribution system models.

5.3 Monitoring Equipment Overview

In general, monitors can be categorized by the types of parameters (contaminants, agents, and characteristics) that the monitor is used to measure. For establishing water quality, the monitors are designed to measure one or more parameters that represent physical, chemical, and/or biological characteristics of the system. Typically, in manual grab sampling programs, hand-held physical and/or chemical parameter measuring devices are used. These hand-held devices are carried to the sampling location along with appropriate containers to collect water samples for performing more complex chemical and biological analyses in a laboratory. The online sampling devices are more complex devices that are designed to automatically measure, record, and display specific physical, chemical, or biological parameters. A brief overview of these devices is presented in the following subsections.

5.3.1 Physical Monitors

Physical monitors are used to measure the physical characteristics of the water in a distribution system. They include a variety of instrumentation that measures various macro characteristics, such as flow, velocity, water level, pressure, and other intrinsic physical characteristics. Examples of intrinsic physical characteristics include pH, turbidity, color, conductivity, hardness, alkalinity, radioactivity, temperature, fluorescence, UV254, and ORP. In general, physical monitors tend to be relatively inexpensive, quite durable, and readily available.

5.3.2 Chemical Monitors

Chemical monitors are used to detect and measure inorganic or organic chemicals that may be present in the water. A wide range of chemicals may be of interest, and a large variety of technologies can be used. A specific technology or multiple technologies must be properly selected for a particular chemical or a group of chemicals of interest. Examples of chemical monitors include, but are not limited to residual chlorine monitor, TOC analyzer, and gas chromatograph/mass spectrometer (GC/MS). Typically, the same general type of technology may be available in either automated online monitoring capability or to support manual grab sample analysis.

5.3.3 Biological Monitors

Biological monitors (bio monitors) include bio-sensors and bio-sentinels. Bio-sensors detect the presence of biological species of concern, such as some forms of algae or pathogens. The general operating principles of bio-sensors may include photometry, enzymatic, and/or some form of biochemical reaction. The bio-sentinels use biological

organisms as sentinels to determine the likely presence of chemical toxicity in a water sample.

In general, bio-sentinels cannot be used to identify the presence of a specific toxic contaminant – rather only that there is some form of toxic contaminant present. Most bio-sentinels operate by observing the behavior of selected organisms. Examples of such organisms include: fish, mussels, daphnia, heterotrophic bacteria, and algae. When the sentinel organism senses the presence of toxicity, it reacts in some unusual manner. Bio-sentinel instruments respond to these reactions and note that an unusual event is occurring. This application is somewhat analogous to the use of indicator organisms (e.g., total coliforms) to indicate the water quality in the distribution system.

While bio-sensors can be directly applied in distribution systems without pretreatment of the sample, the bio-sentinels are typically used in source waters. This is because most organisms are sensitive to the presence of chlorine (or other disinfectants) in the water. Therefore, if a bio-sentinel is proposed to be used for distribution system monitoring, the water must be de-chlorinated prior to entering the bio-sentinel instrument. Dechlorination may affect detection reliability and the chemical characteristics of the water. Also, the bio-sentinels require a protected housing environment along with some sort of nutritional supply to keep the sentinel organism alive and healthy.

5.4 Establishing Monitoring Requirements

Selection of the types, numbers, and locations of monitors is dependent on the nature of the monitoring program desired. These requirements depend upon the overall monitoring objectives and the distribution system site-specific requirements. For example, a monitor used for regulatory purposes may need to monitor different constituents than one used as part of a process control or security system. Similarly, a different monitor may be needed for a utility that uses chlorine as the disinfectant compared to one that uses chloramine. The site-specific monitoring requirements can be evaluated and represented in the following terms:

- monitoring parameters,
- number and location of monitors,
- monitor characteristics (e.g., detection limits, sampling frequency, cost, false negatives/false positives), and
- amenability to remote monitoring and SCADA integration.

These requirements are further discussed in the following subsections.

5.4.1 Monitoring Parameters

The parameters to be monitored depend strongly upon the specific use of the monitor and upon utility-specific situations. For regulatory purposes, the regulations typically specify the minimum set of parameters that must be sampled. For each system, the regulating authority typically also specifies the monitoring locations and frequency. A utility may choose to analyze the water for additional parameters and/or increase the frequency of monitoring in order to address other water quality concerns.

For security monitoring, there are no regulations or standards. Utilities can choose whether or not they want to perform such monitoring and select the parameters they will monitor. Generally, such monitoring will be limited by budgets and by technology. Research and development is being conducted on security monitoring systems, in conjunction with event detection platforms, that measure standard parameters, such as TOC, pH, turbidity, conductivity, chlorine, ORP and temperature. For both process control and security-related monitoring, instrument response time is critical. Therefore, online monitors are typically used in these types of applications. The parameters monitored vary widely depending upon the type of process and/or security monitoring.

The goal of online monitoring for security purposes is to automatically analyze the data to determine (1) whether there is an indication of unusual contamination in the sample; and (2) what the likely contaminant is, based on the water quality signature of these parameters.

5.4.2 Number and Location of Monitors

For selecting monitoring locations in distribution systems, there are two related decisions: (1) how many monitors to place in the system, and (2) where to place them. The number of monitors is generally controlled by the monitoring objective (e.g., regulatory requirement) or by budgetary factors, while the location of monitors is a more complex issue that can be addressed in many ways. For example, for compliance with the TCR and the SWTR, there are specific requirements as to the number of samples that must be taken. For most other uses, the number of sampling points (or the number of monitors installed) is controlled by budgetary and financial constraints and through comparison to the benefits associated with the monitors. The following subsections summarize an approach that can be used when the established objectives do not clearly define the number and location of monitors.

EPA's research in contamination warning systems (CWSs) at the T&E Facility is developing data based on bench- and pilot-scale experiments that reveal how traditional water quality parameters, if monitored online, can serve as triggers for contamination events. Figure 5-1 shows the response of several instruments to the injection of secondary wastewater into a DSS.

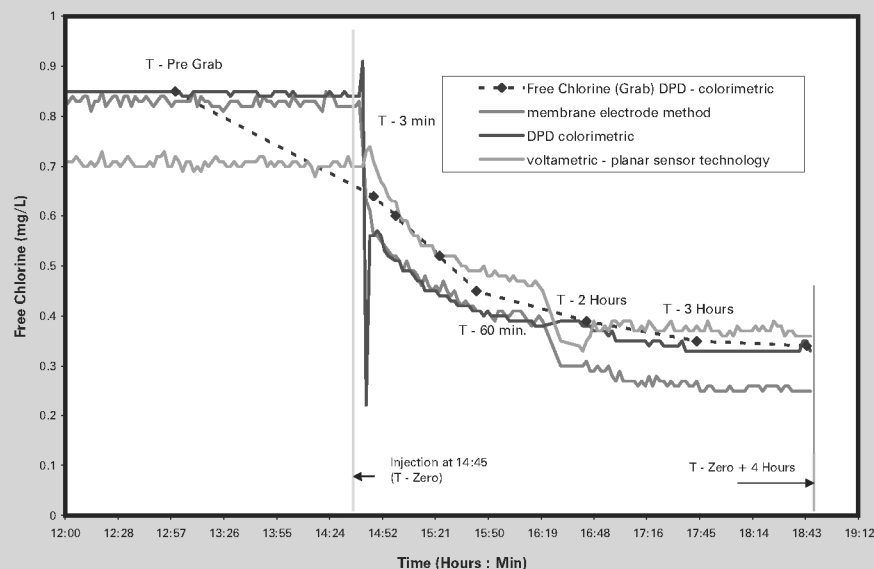


Figure 5-1. Wastewater Injection: Free Chlorine and Associated Grab Sample Results.

5.4.2.1 Number of Monitors

To select the optimum number of monitors for a distribution system, theoretically one can perform a simple cost-to-benefit analysis. If the overall life cycle benefits of each monitor exceed its life cycle costs, analysis would suggest that the monitor is justified. Life cycle costs represent both the capital and operational costs for the monitors. Depending upon the location-specific requirements, as the number of monitors increase, there may be economies of scale or the unit cost may actually increase disproportionately. The unit costs increase when the additional monitors are placed in less convenient locations where servicing and/or data communication costs are higher. Frequently, budgetary constraints may also limit the number of monitors that can be

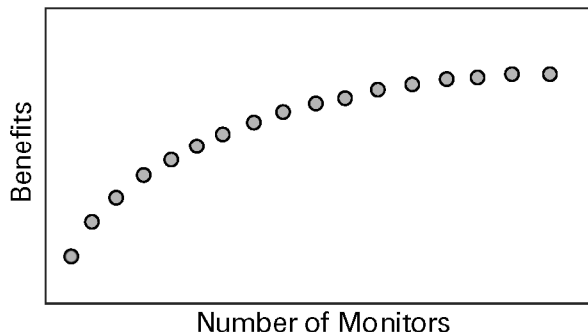


Figure 5-2. Theoretical Example of Benefits from Monitors.

deployed, even if benefits justify their costs.

Figure 5-2 is a graphical representation of benefits associated with increasing the number of monitors in a distribution system. This graph illustrates that typically after a basic network of monitors has been established for a distribution system, the incremental benefits gained by installing additional monitors follow the law of diminishing returns. The actual development of such a graph is difficult because of the need to explicitly quantify benefits. In the case of water security-related monitoring, one could measure the value based on population or sensitive facilities (e.g., hospitals) protected by use of online monitors. For other types of monitoring situations, quantification of benefits is more difficult.

Though a formal cost-benefit analysis may not be feasible, this discussion provides a general framework that can informally guide the design of a monitoring network.

5.4.2.2 Optimal Monitor Locations

Historically, monitors/sensors have been placed in distribution systems to meet regulatory requirements. Their locations have been determined based on ease of access and a general intuitive assessment of representative locations. Lee et al. (1991) proposed a method for locating monitors, based on the concept of coverage, which is defined as the percentage of total demand that is sampled by a set of monitors. Various other researchers further addressed this issue using alternative mathematical methods (Kessler et al., 1998). Though widely cited, these methodologies have rarely been applied in actual practice. However, following the attacks of September 11, 2001, there has been a renewed interest in the development of monitoring technology and placement of monitors in the distribution system as a mechanism for detecting intentional contamination of distribution systems.

Many current studies are applying optimization techniques to determine the optimal placement for monitors in distribution systems based on a defined objective function. Ostfeld (2004) and Ostfeld and Salomons (2004) provide reviews of past work in this area and present example mathematical formulations

A 17th century Italian economist, Vilfredo Pareto, developed a method for comparing alternatives. Based on his work, a situation is defined as being Pareto-optimal if by reallocation you cannot make someone better off without making someone else worse off. This can be applied to evaluating monitors by examining the diagram (Figure 5-3) where various monitoring options are compared in terms of their cost and some measure of effectiveness. Just looking at alternatives A and B, we can say that A is better than B because it costs less and is more effective. By comparing all potential alternatives, we can define a Pareto front. All alternatives located on that front are better than alternatives located to the right and below the front. This provides a useful conceptual mechanism for evaluating alternative monitoring schemes. For additional information on the work of Pareto, see Johansson (1991). For more details on the application of Pareto's concepts in the area of optimization related to water distribution system analysis, see Walski et al., (2003).

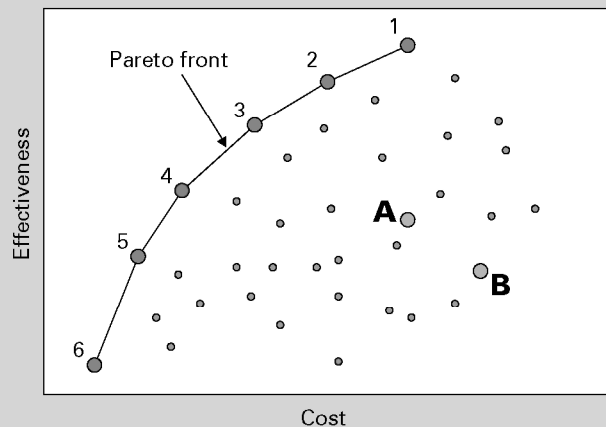


Figure 5-3. Pareto-Optimal Cost Effectiveness Diagram.

using genetic algorithm solution techniques. Their methodology finds an optimal layout of an early warning detection system comprised of a set of monitoring stations aimed at capturing contamination from external sources, nodes, or tanks under EPS conditions. Berry et al. (2004) developed an optimization program that considers the maximum volume of contaminated water exposure at a concentration higher than a defined safe level. The method uses an integer programming optimization technique to place a limited number of “perfect” sensors in the pipes or junctions of a water network so as to minimize the expected amount of exposure to the public before detection, assuming the attack occurs on a typical day.

Watson et al. (2004) use mixed-integer linear programming models for sensor placement over a range of design objectives. Using two case studies, they

Bahadur et al. (2003) describes an approach using PipelineNet in which GIS data and hydraulic model results are used to guide the manual placement of monitors in order to fulfill some general criteria. In a case study conducted with personnel at a water utility, 25 potential monitoring sites were identified and subsequently reduced to two best sites using the GIS/PipelineNet framework. This approach is more closely related to the traditional methods for locating monitors compared to the optimization techniques described in this section.

showed that optimal solutions with respect to one design objective (e.g., population exposed) are typically highly sub-optimal with respect to other design objectives (e.g., time for detection). The implication is that robust algorithms for the sensor placement problem must carefully and simultaneously consider multiple, disparate design objectives.

In general, the optimization methods described above are experimental approaches that have been applied only to hypothetical or small water systems and are based on assumptions about the availability of monitoring technology, ability to define explicit objective functions, and limited incorporation of the variability of water system operation. Further research and development is needed before this technology is ready for routine use.

5.4.3 Monitor Characteristics

The following characteristics of monitors must be evaluated prior to selecting an appropriate device:

- **Minimum detection limit (MDL)** – The minimum detection limit is the lowest concentration or value at which the monitor can dependably detect the constituent of interest. The MDL can vary for different constituents, different technologies, or for different implementations of the same technology and constituent.
- **False negatives/false positives** – Two forms of errors associated with a monitor are false positives and false negatives. A false positive exists when a monitor reports, incorrectly, that it has detected a constituent where none exists in reality. A false negative exists when a monitor reports, incorrectly, that a constituent was not detected when, in fact, it was present. False positives can lead to unneeded responses, and repeated false positives will lead to a lack of confidence in the instrument. Lack of detection associated with a false negative results in no response to a real contamination event and can expose consumers to contaminants in the system.

The heightened level of concern over the need to protect water distribution systems has led to the initiation of research into the development of CWSs for both source and finished waters (Clark et al., 2004a). CWSs are intended to reliably identify low probability/high impact contamination events in source or distributed water. The International Life Sciences Institute (ILSI) developed a report (ILSI, 1999) focused on the development of environmental warning systems (EWSs) for source water. The same development principles apply to distribution systems. EWSs applied to distribution systems are commonly referred to as CWSs. The following design requirements for EWSs were identified by ILSI in their report:

- provides warning in sufficient time to respond to a contamination event and prevent exposure of the public to the contaminant,
- capable of detecting all potential contamination threats,
- remotely operable,
- identifies the point at which the contaminant was introduced,
- generates a low rate of false positive and false negative results,
- provides continuous, year-round surveillance,
- produces results with acceptable accuracy and precision,
- requires low skill and training, and
- be affordable to the majority of public water systems.

A key aspect of an effective EWS will be the need for it to operate in a remote monitoring and reporting mode.

- Sampling frequency – The rate at which a monitor analyzes and reports a value is the sampling frequency. This may vary from a few seconds or less for an instrument such as a pressure gage to an hour or more for instruments that take longer periods to perform the analysis such as a gas chromatograph. For grab sampling, this delay may be even higher. Some instruments can be set for different sampling frequencies. More frequent sampling may result in higher operating costs, shorter battery life, increased data storage requirements, or increased communication needs.
- Amenability to SCADA integration – The monitor's ability to be online and integrated into some sort of SCADA or remote data acquisition system is critical if multiple remote locations are monitored simultaneously. Most current online monitors have analog (e.g., 4-20 mA, 1-20 V) or digital signal (e.g., RS232, RS485) outputs that provide the ability to

remotely collect and store data at a central location for analysis.

- Operation and maintenance requirements – The operational requirements of monitors can vary significantly and may strongly impact the selection process. Issues include the electrical needs, expendable material needs (e.g., reagents, wear related components), temperature and humidity requirements, needs to handle waste streams from the monitor, and other factors related to the housing of the monitor. Similarly, the maintenance requirements of the monitors will also impact the selection process. Issues such as how frequently a technician must service the monitor in the field and the level of expertise required to service the device are important considerations when evaluating monitors.
- Combinations of monitors – The ability of a monitoring system to reliably detect a contamination event generally increases with multiple monitors working in tandem. For example, a single monitor that reports a signal slightly above the noise level may easily be dismissed. However, if multiple monitors at several locations in close proximity or several instruments at the same location monitoring for different parameters all detect a potential event, a more forceful and rapid response is likely. An ongoing area of research is the development of data mining algorithms that can differentiate or detect a signal above background levels that are not normally observed in the monitored system.
- Costs – The cost of monitoring systems can vary over several orders of magnitude. A single simple instrument monitoring for a physical parameter such as conductivity may cost less than \$1,000. The cost of a multi-parameter physical monitor is typically in the neighborhood of \$10,000. More complex instruments such as a TOC monitor or a GC/MS cost in the range of \$25,000 to \$90,000. The cost of more complex instruments or a monitoring station containing multiple instruments can easily exceed \$100,000 in capital cost. Installation and ongoing maintenance costs are frequently site-specific and vary according to environmental conditions.

5.4.4 Amenability to Remote Monitoring and SCADA Integration

For a comprehensive network-wide water quality remote monitoring program, it is essential to ensure that the system and its monitored components are amenable to remote monitoring and SCADA integra-

tion. The SCADA component adds the element of control to the monitored network. Most utilities have some sort of SCADA functionality to automate and monitor the key water treatment and/or distribution operations. The control logic is typically triggered based on a specified time and/or event. For example, the pumps may be set to fill a distribution system tank at midnight and when the tank level monitor detects that the tank is full (an event reported through the SCADA system), the control logic to turn off the pumps is initiated. This type of control logic can be enhanced to perform control functions based on detection of water quality change in the distribution system. However, to achieve this functionality, one needs to understand the following three major components of a remote monitoring and/or control system (or SCADA):

- online sampling instruments (e.g., pH, ORP) and/or control devices (e.g., pump, valves),
- SCADA or remote monitoring network, and
- field wiring and communications media.

These components are discussed briefly in the following subsections.

Electric power is generally required for operating these components. If electric power is not readily available at the desired location where a monitor is to be installed, consider the costs for installing a suitable power apparatus (e.g., a solar panel, battery pack).

5.4.4.1 Online Sampling/Control Devices

Online sampling/control devices can be the most expensive component of a SCADA system. The sensors, switches, monitors, and controllers used in a SCADA system may vary widely, depending upon the parameters that need to be controlled and/or observed. The cost for online sampling devices can range from a few hundred dollars to over \$100,000. Control units such as sample feed pumps or shut-off valves are less expensive (Panguluri et al., 1999). Costs associated with maintenance and calibration of the online sensors when planning the acquisition and implementation of a remote monitoring network should also be considered.

5.4.4.2 SCADA or Remote Monitoring Network

Larger utilities typically use some type of SCADA system for water distribution system control that can easily be integrated to include online sampling instrumentation in a cost-effective manner. Also, recent advances in electronic hardware and software technologies have resulted in several cost-effective SCADA alternatives for smaller systems. A micropro-

Sensors and Transducers: A sensor responds to a physical and/or chemical stimulus, such as thermal energy, flow, light, chemical, pressure, magnetism, or motion. A transducer takes the measured physical and/or chemical phenomenon (e.g., pressure, temperature, humidity, and flow) and converts it to an electrical signal. In each case, the electrical signals produced are proportional to a physical and/or chemical quantity being measured based on a pre-defined relationship. The electrical signals generated by transducers often require “conditioning.” Depending upon the transducer, a signal conditioner can be used to perform one or more conditioning functions, such as noise filtration, amplification, linearization, isolation, and excitation.

cessor-based “smart” SCADA system can be used in remote locations by small system operators where direct online communication is expensive. Smart systems have higher initial costs, but overall costs are reduced since the communication costs (e.g. long-distance phone costs) are negligible because most of the burden is transferred from the main computer to the individual SCADA unit at the remote site (Panguluri et al., 1999). Newer SCADA units are fairly inexpensive, with capital costs ranging between \$500 (PC card-based units and remote data collection nodes) and \$5,000 (independent PC-based full SCADA units).

The data acquisition hardware processes the digital and analog inputs/outputs from various online sampling and control devices. For monitoring systems, the hardware typically processes the analog data measured from various instruments and transfers it to a computer system for display, storage, and analysis. In a monitoring/control system (SCADA) scenario, the hardware would process both analog and digital inputs (typically from a field device) and outputs (to perform control functionality). The application software provides the operator the display, control, and analysis (trends and reports) of collected data.

5.4.4.3 Field Wiring and Communication Media

Depending upon availability, cost, user preference, and the relative location of the sensors to the data acquisition system, the communication media can be either wired (e.g., direct, phone line) or wireless (e.g., radio, cellular). In field environments, distributed input/output (I/O) is typically employed. A remote data acquisition hardware unit employed at the field location performs the appropriate signal conditioning and transmits the data to a central hub. More recently, mesh or grid computing systems are used in remote locations to add redundancy in cases of link failures. The field wiring between the sensor and the remote data acquisition hardware unit is usually direct wire.

Depending upon the area covered and availability, in some cases it may be preferable to use some form of radio communication devices. The available radio communication devices operate mostly in the very high frequency (VHF) or ultra high frequency (UHF) range. The VHF frequencies range between 30-300 megahertz (MHZ) and the UHF frequencies range between 300-1,000 MHZ. In U.S., most of the available VHF/UHF radio frequencies are licensed. The unlicensed bands available include the industrial, scientific and medical device channels with frequency ranges between 902 - 928 and 2,400 - 2,484 MHZ. The unlicensed bands do not have any connection or monthly fee requirements.

Typically, direct wire and phone line (including cellular) communication media are inexpensive. The primary limitations associated with selecting the communication media include installation and operating costs, which can vary between \$200 (for a simple telephone or cellular modem) and several hundred dollars for a satellite-based system per location. Ongoing monthly operating costs can range from \$25 for a phone line to approximately \$200 per month for satellite-based services within the U. S (per monitored location).

5.5 Engineering and Evaluating a Remote Monitoring System

Once all of the basic requirements have been established (e.g., objectives, parameters, location) as outlined in the previous section (Section 5.4) and the requirements indicate a need for a system-wide remote monitoring program for water quality, the following additional site-specific needs should be evaluated for water quality monitoring in a distribution system (Panguluri et al., 1999):

- What are the complexities of the distribution system (size, location)?
- What locations are best suited for sampling and/or control system installation?
- Is sufficient flow and water pressure available for online instruments?
- Is there an existing SCADA system available?
- What types of communication media are available at the selected locations?
- How many parameters are going to be monitored and/or controlled at each location?
- What other site-specific information (e.g., availability of power, access, security) will be needed?

Additional factors to be considered are (Haught and Panguluri 1998):

- system features (e.g., ease of operation, customization, networkability, operator security),
- cost (initial, training, service agreements, and operation and maintenance), and
- vendor support (hardware and software upgrades and remote diagnosis).

It is important that each site is evaluated individually for appropriate SCADA system selection. The cost of SCADA software has plummeted over the past few years. For example, the cost of one commercially available graphical (Windows-based) SCADA software package has dropped from \$30,000 in the early 1990s to \$2,000 today.

Prior to selecting and implementing a remote monitoring network, one should evaluate the options carefully. Engineering a remote monitoring system is a difficult task that typically involves many factors: multi-dimensional objectives, changing needs, rapid

Besides the aforementioned immediate needs (e.g., ease of operation, customization, networkability), SCADA system features include:

- Scalability: This allows for future growth with respect to addition of I/O blocks with more channels or advance capabilities. These I/O channels are used to communicate with various field monitoring instruments (sensors) and control devices.
- Local Memory: The SCADA hardware must also contain sufficient local memory to store the monitored data for extended periods of time in case of communication failures.
- Remote operation and diagnosis: In the event of brownouts or blackouts, the field SCADA units should normally self-boot upon resumption of power supply. The field SCADA units should also allow for remote diagnosis.
- Call-out feature: This feature allows the system's software to notify appropriate personnel if problems develop with a treatment system or water quality. This feature can greatly enhance operator response in emergency situations and prevent costly shutdowns and loss of water and/or water quality.
- Open Database Connectivity (ODBC): This feature allows for open communication with other databases and tools that can be integrated to provide additional features. The data then can also be used for network modeling.

technological change, conflicting technical claims, and budgetary constraints. The following subsection presents general methods for evaluating and assessing alternatives followed by a set of specific criteria for evaluating alternative monitoring systems.

5.5.1 Remote Monitoring System Evaluation

In order to justify a remote monitoring system and to select the best monitoring system, it would be ideal if one could evaluate the benefits derived from monitoring and compare them to costs and choose the system that maximizes net benefits subject to budgetary constraints. Depending on the uses of the monitoring data, monitoring benefits may be associated with:

- reduced risks from an intentional or accidental contamination event,
- improved understanding of the variation in water quality of a distribution system,
- enhanced operation if the data are used as part of a process control system, and
- increased compliance if the information is used for regulatory purposes.

5.6 Monitoring Case Studies

EPA has conducted research into the use of remote monitoring and control technology alternatives for many years. These projects have involved both water treatment systems and water distribution (Clark et al., 2004b). The agency's first research project that incorporated real-time monitoring at a remote location was conducted at the T&E Facility. The initial research was focused on evaluating SCADA systems for small drinking water package plants. The goal was to demonstrate that SCADA systems could be used to monitor and control several small plants remotely from a centralized location at one time (Haight and Panguluri, 1998). The following case studies represent some of the highlights of the research and collaboration with different water utilities.

5.6.1 Rural Community Application

In May 1991, EPA provided funding to support a research project titled "Alternative Low Maintenance Technologies for Small Water Systems in Rural Communities" (Goodrich et al., 1993). This project involved the installation of a small drinking water treatment package plant in a rural location in West Virginia. The primary objective of this study was to evaluate the cost-effectiveness of package plant technology in removing and disinfecting microbiological contaminants. The secondary objectives of this project included: remote monitoring and automation of the system to minimize the O&M costs, assessment of the community's accep-

tance of such a system, ability to pay, and the effect of the distribution system on water quality at the tap. The following is a brief summary of the overall project.

The treatment system was located in rural Coalwood (McDowell County), WV, approximately 12 miles from the McDowell County Public Services Division office. Prior to 1994, an aerator combined with a slow sand filter was being used for water treatment at this site. This combined unit had been operational for over 30 years and needed substantial repairs. The water flowed by gravity from an abandoned coal mine to an aerator built over a six-foot-diameter slow sand filter. A hypochlorinator provided disinfection of the treated water, and the water flowed by gravity through the distribution system to the consumer. The volume of water from the mine was considered sufficient for the small rural community.

Based on a review of existing technology, EPA determined that a packaged ultrafiltration (UF) system would be ideally suited for this location. In 1992, a UF unit was purchased and installed at this site. In 1996, EPA developed, installed, and tested a remote monitoring system at the site. The system used commercially available hardware along with EPA-developed software. The software was not user-friendly and the overall cost of ownership was very high. Therefore, in 1998, EPA updated the SCADA system with a scalable commercially available off-the-shelf, user-friendly SCADA system. The total cost (including instrumentation, technical support, training, and set-up) was approximately \$33,000. EPA installed similar SCADA systems at Bartley and Berwind sites in McDowell County, WV, for remote monitoring of water quality.

5.6.2 Washington D.C. Remote Monitoring Network

Following a number of coliform violations, EPA's Region 3 office directed the Washington D.C. Water and Sewer Authority (WASA) to implement a number of corrective actions for its water distribution system (Clark et al., 1999). Remote monitoring of water quality parameters within the distribution system was identified as being one possible method for identifying water quality problems. Consequently in 1997, EPA initiated a study to install a remote network at various locations in Washington D.C. to monitor water quality within the distribution system (Meckes et al., 1998). The WASA staff teamed with EPA to select appropriate locations within the distribution system for installation of online sampling stations. Following are some of the study objectives:

- development of methods to monitor real-time water quality at various locations within the

distribution system,

- field evaluation of sensors and remote monitoring technologies for inclusion in the network,
- development of effective methods to publish real-time data that enhanced consumer confidence,
- evaluation of costs associated with implementing such systems, and
- identification of potential problems and suggestions for remedial actions when implementing remote monitoring networks.

Free chlorine, pH, temperature, and turbidity were selected as the monitored parameters based on the availability of online sensor technologies. The selection was based on the premise that these were parameters which could be reliably monitored continuously and the selected instruments required limited maintenance. Additionally, WASA used their SCADA system to track various operating parameters within the distribution system. During the evaluation, it was clear that use of the existing SCADA system to manage the monitored data provided clear advantages over other available systems. Using the existing SCADA system minimized long-term on-site support costs.

After suitable location(s) were identified, customized sampling and monitoring systems were built. The remote monitoring system in Washington D.C. was implemented in three phases. In the first phase, a remote monitoring system was installed at the Fort Reno #2 tank (Figure 5-4), which provided security and easy access to the distribution system. Subsequently, based on initial success at this location, two other sites (Bryant Street and Blue Plains) were selected and added to the remote monitoring network in the second phase. The third phase involved the development of a Web-based application to publish the real-time data in order to enhance consumer confidence.

Figure 5-5 shows the relationship between the SCADA system and the transmission of the data. Al-

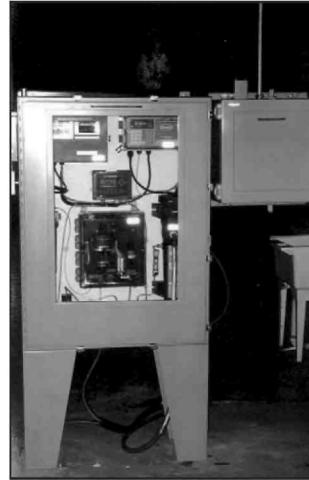


Figure 5-4. Fort Reno #2 Remote Sampling System.

though WASA's SCADA system used a proprietary operating system, it provided a personal computer (PC) link which was used to dump data into a regular PC for further processing. The hardware-based feature enabled tight security; an authorized end user could only copy the relevant data published on the PC and could not directly access the SCADA system. This feature also eliminated any potential interference between the sampling system data and other distribution system operations data. Unfortunately, the EPA funding for this study was terminated and, as a result, the systems and the Website are currently not operational. The overall project, however, did demonstrate that such systems could be developed and operated. Figure 5-6 shows some of the output data for the Fort Reno tank which indicates the loss of disinfectant chlorine levels at night. Clearly, this type of information can be used to improve system operations to better maintain the water quality.

5.6.3 Tucson Water Monitoring Network

Based on a grant received from the EPA's Environmental Monitoring for Public Access and Community

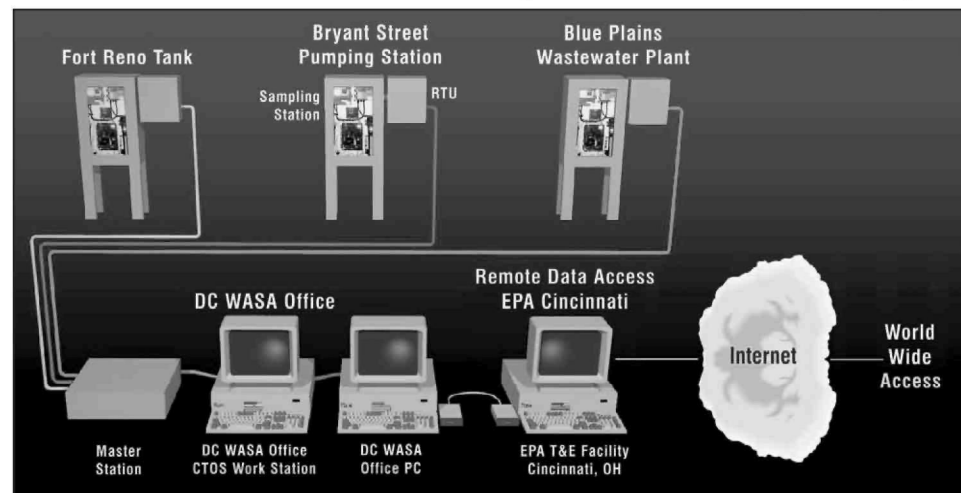


Figure 5-5. WASA Remote Monitoring System Layout and Data Transmission Scheme.

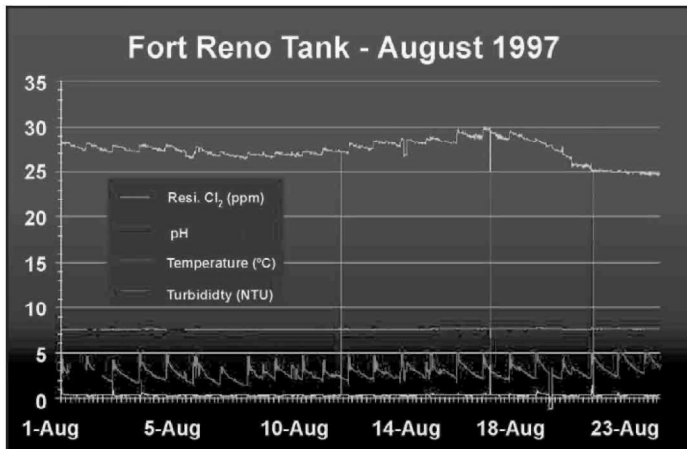


Figure 5-6. Monitoring Data for Fort Reno Tank.

Tracking (EMPACT) Program, the city of Tucson implemented a comprehensive water quality monitoring program. The city's EMPACT goals included the following: implementing enhanced monitoring of the utility's potable distribution system, providing the community with near real-time water quality information on Tucson Water's Website (www.cityoftucson.org/water), and creating community partnerships to better inform water consumers about water quality and resource issues. The water quality monitoring and data collection tools provided through EMPACT also enables the utility to track and respond to real-time changes in system water quality.

Tucson Water's distribution system consists of one central drinking water distribution system that serves the majority of the customers and ten isolated drinking water distribution systems. All eleven drinking water distribution systems cover a service area of 300 square miles and serve 680,000 customers in the Tucson metropolitan area. The two types of source water that supply the central distribution system are native groundwater and renewable recharged surface water from the Colorado River. The source water that supplies the ten isolated distribution systems is groundwater.

For the purposes of monitoring, the central distribution system is divided into ten water quality zones and each isolated distribution system is considered an individual water quality zone. Figure 5-7 shows the zone map. A water quality zone is defined as an area of the distribution system that is similar in water quality characteristics, water pressure, geographical, and political boundaries. Each water quality zone has a set number of dedicated sampling stations and points-of-entry (POE). The dedicated sampling stations monitor the quality of the drinking water in the distribution system before delivery to the customer. The POEs are usually individual wells that represent the water quality of a single well or in a few

cases, combined POE systems that represent the collective blended water quality from a group of wells that directly supply Tucson's drinking water.

In total, there are 262 dedicated sampling stations and approximately 154 active POEs located within the multiple distribution systems. In addition, 22 online water quality stations (for monitoring: chlorine residual, total dissolved solids, pH, and temperature) are located throughout the central distribution system at strategic locations, such as reservoirs, well sites, and booster stations, as one of the primary objectives of the EMPACT program.

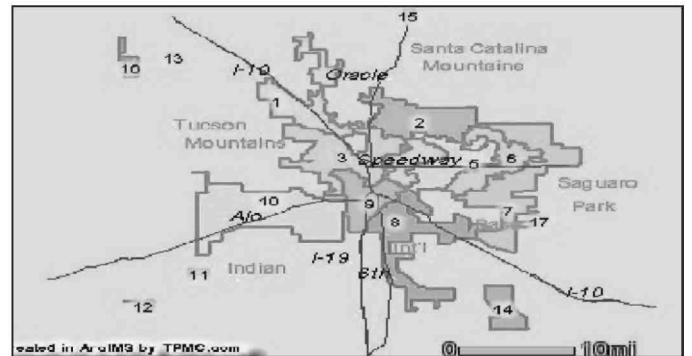


Figure 5-7. City of Tucson Water Quality Zone Map.

Figure 5-8 depicts a continuous water quality monitoring station. The monitoring frequency ranges from tri-annually (for grab sample locations) to every 60 seconds (for continuous monitoring stations), depending on the location and specific monitoring program that is being utilized for that location.

The comprehensive water quality monitoring program encompasses the entire distribution system. Source waters are monitored and sampled according to the Arizona Department of Water Resources and the

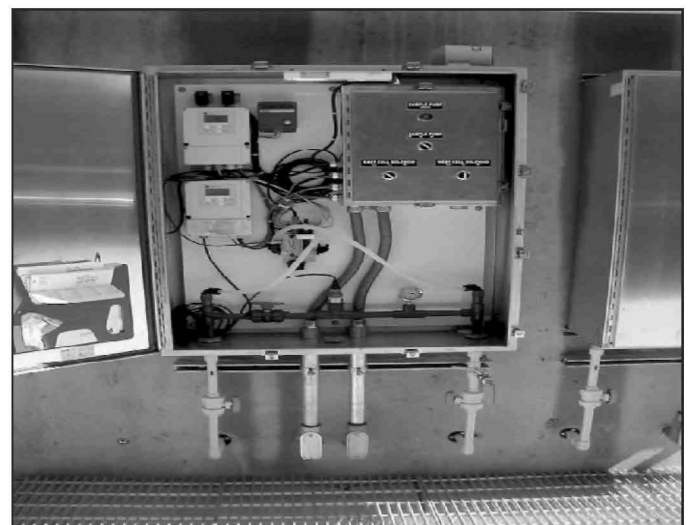


Figure 5-8. Continuous Water Quality Monitoring Station.

Arizona Department of Environmental Quality (ADEQ) regulations, while the drinking water is monitored according to EPA and ADEQ regulations and drinking water standards. Drinking water is also evaluated against a set of consumer-established water quality goals. Special-purpose samples are taken to characterize and track changing trends in water quality for both source water and drinking water. All data sets are utilized to track and monitor changes in water quality to learn the baseline water quality operating parameter levels and also to be able to identify and react appropriately when a contamination event occurs. Most of the analysis is conducted by the utility's water quality laboratory and all the results are tracked through the Water Quality Management Division.

All 262 dedicated sampling locations are monitored at least once each month for total coliform and chlorine residual, while 26 other parameters are monitored once every three months. Based on the water quality measurements collected each month from these 262 sampling locations, the trends in water quality conditions are determined for each water quality zone and for the distribution system as a whole. This information can be found on the aforementioned Web site in the Water Quality section under Tucson's Water Quality and Water Quality in My Neighborhood links. The water quality information displayed on two interactive maps shows data charts and tables for each location that is sampled under the Water Quality program. In addition, the information provided to all Tucson water customers in the annual water quality report or consumer confidence report is based on POE monitoring data.

5.7 Summary and Conclusions

Distribution system monitoring is intended to identify the spatial and temporal variations in water quality that take place in a drinking water system. Monitoring data can be used to satisfy various objectives, such as regulatory requirements, security requirements, or process control requirements. The costs of implementing such a system can best be justified if the resulting data can be used for more than one of the aforementioned objectives.

A monitoring program can implement either routine grab sampling or continuous monitoring. A combined approach, utilizing both continuous and grab sampling data, may prove to be very effective as the basis for a comprehensive system-wide monitoring plan. In the past, distribution system online monitors were typically housed in a controlled environment with sample lines from the distribution system to the instrument. This resulted in most instrumentation being located at facilities such as tanks and pump stations. The instrumentation was sometimes con-

nected to a SCADA system, so that results could be communicated to a central office. Recently, some instrumentation has been designed for installation in manholes or for direct insertion into water distribution system pipes.

Vulnerability assessments performed by utilities and various research studies have identified that water distribution systems are vulnerable to intentional or accidental contamination. In addition to hardening systems to make it more difficult to contaminate a system, monitoring as part of a CWS has emerged as a logical approach to cope with potential contamination events. Monitors can also be used in a distribution system to provide real-time or near real-time information on water quality. The data can then be used to control treatment processes at a treatment plant or in the water distribution system. However, this type of program may not be practical for small systems.

SCADA is widely used in industrial environments and by larger water utilities to control and monitor their individual facility operations. However, water utilities typically do not use available SCADA systems for conventional water quality monitoring. Water utilities typically monitor water quality parameters by performing grab sampling on a scheduled or random basis that provides a periodic snapshot of the overall system. Current drinking water regulations require all public water systems to implement water quality monitoring for total coliform to ensure that good quality water is provided to consumers (EPA, 1996). Since the regulations do not clearly specify that real-time monitoring of water quality is required, utilities have been reluctant to install and operate such devices.

After the events of 9/11, utilities have become more interested in the potential for continuous water quality monitoring. SCADA systems can assist in this function by constantly monitoring water quality within drinking water distribution systems. These systems can potentially reduce the risk of security related threats or even non-security related threats, and detect undesirable water quality changes within a system (Meckes et al., 1998).

Users should evaluate monitoring data appropriately for errors and inconsistencies before commencing actions based on acquired data. Each component in a monitoring system is a potential source of error. For example, a remote monitoring system could have data errors for one or more of the following reasons: instrument errors and spikes, SCADA data errors related to system failure, backfilling due to communication failure, timing errors, or missing data. It is important to validate data and understand routine changes in water quality due to system-specific operations.

Monitoring equipment should be chosen appropriately after establishing the monitoring requirements. The individual monitor characteristics, costs, and amenability to SCADA integration are key to effective implementation. Each system should be individually examined and engineered for implementation.

The monitoring case studies presented in this chapter demonstrate the manner in which effective monitoring systems can be implemented in small, medium, and large distribution systems. If the data are used for responding to a contamination threat, it is important to understand the movement of water in the system.

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Chapter 6

Geospatial Technology for Water Distribution Systems

Section 6.1 provides a brief summary of the history and development of geospatial data management based on information extracted from many sources. This history is included in order to provide a context for the current geospatial data management methodologies in use today by utilities. Readers who are already familiar with the history may choose to skip Section 6.1 of this chapter.

Geospatial data identifies the geographic location and characteristics of natural or constructed features and boundaries on the earth. This information may be derived from various sources of data, including remote sensing, mapping, and surveying technologies. More simply, geospatial data is any information in or on the earth that has a “where” component. This can be a house address, a street intersection on a map, a pump station with a coordinate location stored in a facilities list, or the location of the sampling tap on a diagram of a pump station. Thus, every object has a geospatial data component based on its location.

Geospatial data provides a mechanism for incorporating geographic locations of various functions and facilities in a distribution systems analysis. The cost of incorporating map data into the water distribution systems discipline is decreasing, which enables a wider audience of users to perform powerful spatial analyses over time, such as master plan development, pipe break analysis, and locational information on sensitive subpopulations (e.g., nursing homes, schools). As these tools and datasets become more commonly used and shared among engineers, new efficiencies will be realized that will have a positive impact on water distribution system management.

Water systems are by nature quite geographically extensive and the location of a particular component or feature may significantly affect its performance. Source watersheds can cover hundreds or thousands of square miles. Similarly, distribution systems can cover vast areas. The operation of a water system entails moving water from one location to another. Elevation (Z), the third dimension of location (along with the X and Y dimensions of a Cartesian coordinate system), is an important factor in designing and operating a water system. This illustrates that the management of a water system is inherently a geospatial issue.

Because of the spatial nature of water systems, many aspects of managing a water system consist of using, managing, and displaying geospatial data. This has

led to a variety of mechanisms ranging from maps and plans to sophisticated, computerized database management systems. The following is a list of some of the computerized data systems that water utilities typically use for managing their spatial data. These systems will be discussed in greater detail later in this chapter.

- GIS – Geographic Information System.
- CADD – Computer-Aided Design and Drafting.
- AM/FM – Automated Mapping (or Asset Management)/Facilities Management.
- CIS – Customer Information System.



- DEM – Digital Elevation Model.
- GPS – Global Positioning System.
- SCADA – Supervisory Control And Data Acquisition.
- LIMS – Laboratory Information Management System.
- LIS – Land Information System.
- RDBMS – Relational Database Management System.
- SDMS – Spatial Data Management System.

6.1 History of Geospatial Data Management

Geospatial data is of interest in many professional fields and each of these fields has approached the issue of using and managing geospatial data in a different manner. Examples include the following:

- Cartographers concentrate on making maps.
- Surveyors emphasize accurate capture of locational information on natural and manmade land features.
- Engineers use spatial data to draw construction plans and, more recently, use it as input for various types of models.
- Planners use maps and spatial data to assess growth and to determine the suitability of land to support a particular type of development.
- People in the public works area are concerned with managing assets such as streets, sewers, and water lines, which all have a spatial component.
- Fields such as the military, engineering, mining, and hydrology are interested in topographic (elevation) data.

As a result of these varying interests in “spatially arrayed data,” the tools and methodologies for managing these data have evolved from many directions and recently there has been a significant move towards integrating the basic concepts. A brief history of geospatial data management is presented below, organized by the various disciplines that have influenced this field. The needs of the water industry in the spatial arena cross each of these areas. Geospatial data management in the water industry will be discussed in greater detail in a later section of this chapter.

6.1.1 Mapping, Surveying, and Remote Sensing

Mapping is the oldest of the geospatial disciplines. Examples of maps date back many millenniums. A wall painting, dating back to around 6200 B.C. in Turkey, depicts the positions of the streets and houses of the town together with surrounding features such as the volcano close to the town. The Babylonians produced clay tablets containing maps that date back to around 1000 B.C. Other early maps were prepared by the Egyptians and Chinese (O'Connor and Robertson, undated).

Many of the advances in map making are attributed to the Greeks. Around 350 B.C., Aristotle argued that the earth was a sphere and around 250 B.C., Eratosthenes accurately calculated the circumference of the earth. In 140 A.D., Ptolemy's eight-volume *Guide*

to Geography was written and provided the basic principles of cartography. It introduced the concept of map projections and attempted to map the known world, giving coordinates of the major places in a system akin to the present day latitude-longitude system. This document served as the definitive reference on geography for over a thousand years and was later translated into Latin and printed in 1475.

The 16th century saw the introduction of globes and many improvements in the mathematical basis of cartography. Gerardus Mercator developed a wall map of the world in 1569 on 18 separate sheets (see Figure 6-1). In the “Mercator projection,” lines of longitude, lines of latitude, and rhomb lines all appear as straight lines on the map. This projection was a great aid to navigators and is still in use today. With the basis of cartography well in hand almost 500 years ago, the cartographic methodologies continued to evolve. Additionally, emphasis was placed on methods of accurately establishing the coordinates of places of interest. This led to the field of surveying and, more recently, the field of remote sensing.



Figure 6-1. Mercator's Map of the World in 1569 (Whitfield, 1994).

“Surveying is the science and art of measuring distances and angles on or near the surface of the earth. It is an orderly process of acquiring data relating to the physical characteristics of the earth and in particular the relative position of points and the magnitude of areas. Evidence of surveying and recorded information exists from five thousand years ago in places such as China, India, Babylon, and Egypt” (Queensland Government, undated). Some key inventions in the area of surveying include the following:

- Knotted ropes – Measuring device developed by the Egyptians and used in construction of the pyramids.
- Levels – Mechanism developed by the Egyptians composed of a hanging “plumb bob” used to establish a level surface.

- Magnetic compass – Device for determining north direction. Developed by Chinese circa 200 B.C. and composed of a magnetic “lodestone.” Later used by Chinese for navigation.
- Theodolite - An instrument, graduated in 360 degrees, used in the mid-1500s by an Englishman, Leonard Digges, to measure angles.
- Alidade and Plane table - Sighting mechanism and flat table developed in 1590 for mapping the surface features of the earth. Attributed to Jean Praetorius.
- Quadrant and Sextant - The quadrant is an apparatus developed in 1730 by John Hadley for measuring angles of celestial bodies. This led to the development of the sextant, which is a precision instrument made from brass or aluminum that is used for ocean navigation where celestial observations are taken to plot a ship’s position.
- Transit - The transit is used to measure vertical and horizontal angles and may also be used for leveling; its chief elements are a telescope that can be rotated (transited) about a horizontal and about a vertical axis, spirit levels, and graduated circles supplemented by Vernier scales. Attributed to W.J. Young in Philadelphia in 1831.
- Electronic Distance Measurement (EDM) – Starting in the 1950s, electronic distance measuring instruments were developed and have now largely replaced traditional methods for measuring distance. Horizontal distances are measured using a variety of instruments that employ a laser beam aimed at a reflector station. Low-cost instruments that employ sound waves or infrared beams are also available.
- GPS - The use of GPS in surveying procedures is the most recent and revolutionary change to influence land measurement. GPS was designed and built and is operated and maintained by the U.S. Department of Defense. Originally called the Navstar GPS, it was first brainstormed at the Pentagon in 1973. In 1978, the first operational GPS satellite was launched; by the mid-1990s, the system was fully operational with 24 satellites. The basic principle behind GPS is the measurement of distance between satellites and the receiver. The distance to at least 3 satellites must be known in order to find out a position. Satellites and receivers generate duplicate radio signals at exactly the same time. As satellite signals travel at the speed of light (186,000

miles per second), they only take a few hundredths of a second to reach the GPS receiver. This difference and the speed at which the signal travels is used in the equation to find out the distance between the GPS receiver and the satellite (Radio Shack, 2004). GPS is now also being used to provide information on elevations.

Local governments frequently store survey information on parcels in an LIS. This information can include property ownership, construction date, land assessment, and land taxation. This information may be linked to a computerized database system for storing the geographic coordinates of the parcels.

Remote sensing refers to imagery from airplanes or satellites. Some early examples of remote sensing include: aerial photography from a balloon in 1859 by Gaspard Felix Tournachon in an attempt to conduct a land survey; use of light cameras attached to pigeons in Bavaria in 1903 to monitor troop positions; photographs of San Francisco following the 1906 earthquake by George Lawrence from a kite; and the work of a photographer who accompanied Wilbur Wright on one of his first demonstration flights in 1909. More serious aerial photography was conducted during World War I and II and during the Cold War period.

Aerial photography has become a staple item in the development of maps and documentation of land use changes. The National Aerial Photography Program (NAPP) is an interagency Federal effort coordinated by the USGS, which uses NAPP products to revise maps. Other agencies have varied uses for these photographs, which are taken on a 5- to 7-year cycle and produced to rigorous specifications. The NAPP effort encompasses the entire lower 48 states and Hawaii. The photos are acquired from airplanes flying at an altitude of 20,000 feet using a 6-inch focal length camera resulting in a scale of 1:40,000. Each 9-inch by 9-inch photo (without enlargement) covers an area of slightly more than 5 miles on a side. The NAPP effort began in 1987 and replaced the National High Altitude Photography (NHAP) program which was initiated in 1980. Strict specifications regarding sun angle, cloud cover, minimal haze, stereoscopic coverage, and image inspection were followed and all NAPP photography is cloud-free (USGS, undated).

Satellite remote sensing can be traced to the early days of the space age (National Aeronautics and Space Administration [NASA], undated). On April 1, 1960, the Television and Infrared Observation Satellite (TIROS 1) was launched, which proved that satellites could observe Earth’s weather patterns. In 1966, the Environmental Science Services Adminis-

tration (ESSA) Satellites I and II gave the United States its first global weather satellite system. In 1972, NASA began the Landsat series with the launch of the Earth Resources Technology Satellite 1, which was later renamed Landsat 1 by NASA. Figure 6-2 illustrates an image derived from Landsat. Subsequently, U.S. governmental satellites, such as Landsat 7, are still gathering consistently calibrated imagery of the earth under the Earth Observation Satellite (EOSAT) program. Satellites of other governments (SPOT-France) and private satellites (GE, Digital Globe) have expanded the routine availability of imagery, and further enhanced the resolution of the data collected.



Figure 6-2. Landsat Thematic Mapper™ Images of the Missouri River Floodplain Near Glasgow, Missouri. (USGS, 1993).

6.1.2 CADD

Over the past quarter of a century, CADD has revolutionized the way in which engineers and architects perform their work. The basis for CADD was laid by Ivan Sutherland's 1963 Ph.D. thesis at Massachusetts Institute of Technology (MIT) titled, "Sketchpad: A Man-machine Graphical Communications System" (Sutherland, 2003). Sutherland used a lightpen to create engineering drawings directly on the Cathode Ray Tube (CRT). His thesis laid out virtually all of the graphical human interface issues. Sketchpad pioneered the concepts of graphical computing,

The acronyms CAD, CADD, CAM, and CAE refer to "computer aided" methodologies used in various fields of engineering. CAD can stand for "computer aided drafting" or "computer aided design". CADD can mean "computer aided design and drafting" or "computer aided drafting and design". CAE refers to computer aided engineering and CAM refers to "computer aided manufacturing". The fields of CAD, CAM and CAE overlap and are frequently lumped into a single field of CAD/CAM/CAE.

including memory structures to store objects, rubberbanding of lines, the ability to zoom in and out on the display, and the ability to make perfect lines, corners, and joints. This was the first GUI long before the term was coined.

In the late 1960s and early 1970s, several companies were founded that developed and commercialized the concepts of CADD. In the 1980s, Autodesk (maker of AutoCAD) and Bentley Systems (Microstation) were founded and led to the wider availability of CADD on personal computers. Later in that decade, Parametric Technology Corp. produced a 3-dimensional design system.

6.1.3 GIS

GIS represents computerized systems for the storage, retrieval, manipulation, analysis, and display of geographically referenced data (Mark, 1997a). Though the term GIS was first coined by Roger Tomlinson, director of the Canada GIS in the early 1960s, many of the concepts of GIS lie in the earlier fields of mapping and cartography. There are several fields and institutions that contributed to the GIS area in a non-linear manner over the past 40 years, resulting in the very powerful and widespread use of GIS today. Figure 6-3 shows the typical inputs and results of current GIS packages.

The development of the Geographic Base File/Dual Independent Map Encoding (GBF-DIME) files by the U.S. Census Bureau in the 1960s was the first large-scale use of digital mapping by the government. This system led to the production of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER) files. Important geographic work was also being done at universities throughout the 1950s and 1960s. A grid-based mapping program called Synagraphic Mapping (SYMAP), developed at the Laboratory for Computer Graphics and Spatial Analysis at the Harvard Graduate School of Design in 1966, was widely distributed and served as a model for later systems. Output from SYMAP was on a line printer. A companion program called SYMVU allowed for mapping of topographic and other data using a pen plotter.

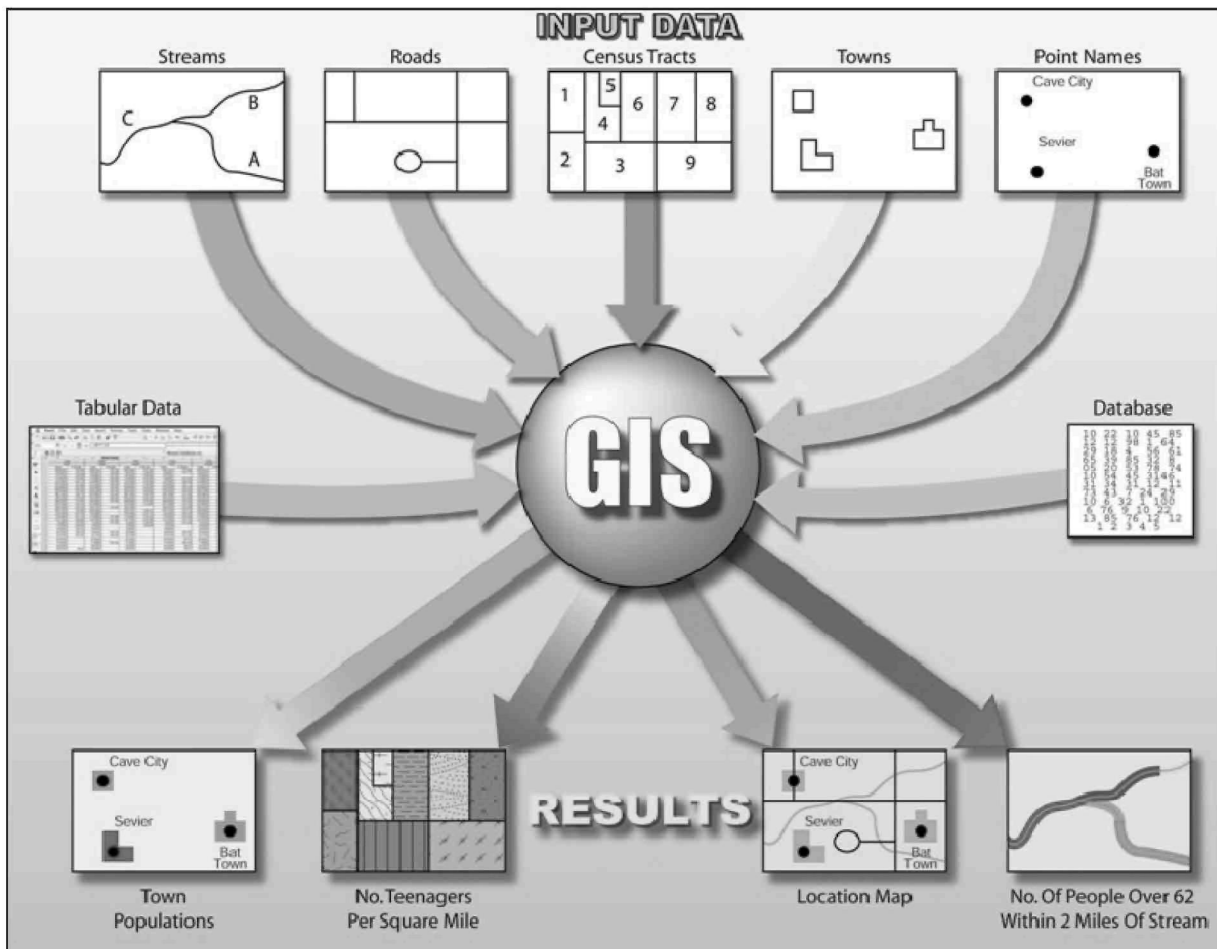


Figure 6-3. Typical Inputs and Results of Current GIS Packages.

From an application viewpoint, much of GIS modeling technology, as it is used today, is largely an outgrowth of planning approaches that are based on the work of Ian McHarg, as articulated in his book *Design with Nature* (McHarg, 1969). His manual methods involved overlaying a grid on the area to be studied, comparing and combining values for different types of attributes in a grid cell to determine the suitability of each grid cell for various uses. Attributes could include characteristics such as land slope and soil attributes.

He demonstrated this process in his book by creating maps of different attributes on transparencies with the darkness proportional to the degree to which that attribute would support a particular use. For example, significantly sloping land would be represented as dark areas because it is difficult to build under these circumstances. Then the reader could physically overlay the transparencies and select the lighter areas which were most appropriate for development. When computerized, this became the basis of the common overlay analysis of GIS technology, which served as the basic modeling technology of GIS for many years.

Another source for GIS technology was computerized

photogrammetry and surveying. In the early 1960s, the desire to manipulate spatial data in a computer led to such well-known civil engineering programs as Coordinated Geometry (COGO), developed at MIT for calculating surveying analyses on coordinate data. At the same time, the concept of the Digital Terrain Model (DTM) was developed, in which the computer would be used to store a digital database representing the earth's surface (see the next subsection for more details on DTM).

In the past decade, development within the GIS community has been primarily associated with commercial enterprises that develop and market GIS software. Companies such as ESRI, Smallworld, Intergraph, Bentley, MapInfo, and AutoCAD dominate the GIS field today. Early important public domain or academic GIS packages such as Geographic Resources Analysis Support System (GRASS), developed by the U.S. Army Corps of Engineers and Clark University, have been largely replaced by the commercial software packages.

6.1.4 DEMs

DEMs and DTMs refer to representation of ground surfaces in a computer. Over the past 40 years, they

have been used to support applications such as highway design, sewer design, hydrologic analysis, mining calculations, and military applications (such as part of a guidance system for missiles). Various methods utilizing regular/irregular grids and triangulated irregular networks (TIN) (Mark, 1997b) have been employed to provide efficient representations of surfaces. DEMs have become a regular feature of today's GIS packages. DEM databases are readily available for most of the U.S. from USGS and other sources. Figure 6-4 depicts a DTM output.



Figure 6-4. Digital Terrain Model of Mount St. Helens after Eruption in 1980 (R. Horne, 2004).

6.1.5 Database Management Systems

Spatial data is composed of two forms of information: geographic coordinates and attribute information. As an example, in order to represent a water main, geographic information describes the coordinates of the start and end of the pipe and any curves or bends in the pipe. Attribute information may include the pipe diameter, length, material, age, and other data of interest. Typically, attribute data are stored in a relational database system that may be part of a GIS or an asset management system. The Relational Database model for database design was invented by Dr. E.F. Cobb in 1969 and published in *Computer World* in 1985. A relational database system is composed of a series of tables that are related through keywords. This model is considered to be highly efficient and minimizes errors.

6.1.6 Facility Management

Facilities management (or asset management as it is frequently called today) pertains to use of computer database and mapping technology to store and manage information related to physical assets in a water system. In the 1980s, the term AM/FM was used to describe the automation of mapping and the management of facilities represented on those maps. This typically involved the integration of CAD

technology and database management technology. In addition to the water industry, AM/FM was used by the electric and gas industry, telecommunications industry, and other industries that maintained physical networks. In the 1990s, the focus of facilities management both shifted and expanded to encompass a broader management of geographic spatially arrayed data that are used and maintained by the various types of utilities. This shift brought a closer interdependence to the GIS field and frequently this broader area is now referred to as AM/FM/GIS (Cesario, 1995) or even more broadly as Geospatial Information Technology.

6.2 GIS Principles

Understanding the basic principles behind geographic information systems is difficult because of the breadth of the field, the rapid change in technology, and the lack of standardization for terminology. This section provides a general overview of the most significant GIS principles.

6.2.1 GIS Features

A GIS is composed of a group of objects or features that have both a locational description and a description of their characteristics or attributes. For example, a water tank can be identified by its location in terms of latitude-longitude or other coordinate systems and its characteristics, such as diameter, height, and type of construction. Similarly, a pipe can be described by its route, diameter, length, material, and age. More importantly, these attributes can be stored, updated, and analyzed in a database over time.

Geographic features are stored in three general ways: vector, raster, or TIN. Though a geographic feature can frequently be stored in more than one way (e.g., as a vector or as raster), typically there is a preferred way to store each piece of information. Under the general area of vector representation, features can be stored as points, lines, or polygons. Figure 6-5 illustrates the three types of features in an example map of a water

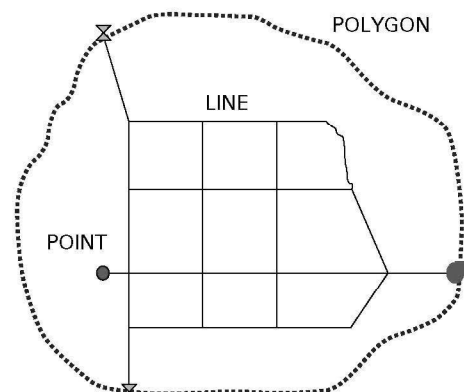


Figure 6-5. Map of Pressure Zone Showing Three Types of GIS Vector Data.

distribution system pressure zone. Points are geographically represented as a single set of coordinates in two or three dimensions. A line can represent either a single, straight-line segment, identified by the coordinates of the two end points, or a series of connected line segments to represent a curved line. A polygon is defined by a closed set of line segments and identifies the area contained within the defined outer boundary.

Raster data most commonly refers to a set of data that has been defined in terms of a regular square or rectangular grid system that is tied to a geographical coordinate system. Each grid cell can have one or more characteristics assigned to it. As an example of a raster data set, Figure 6-6 illustrates land use information derived from a satellite that is represented as a raster database. Other methodologies for storing raster data include scan lines and other regular grid cell configurations.

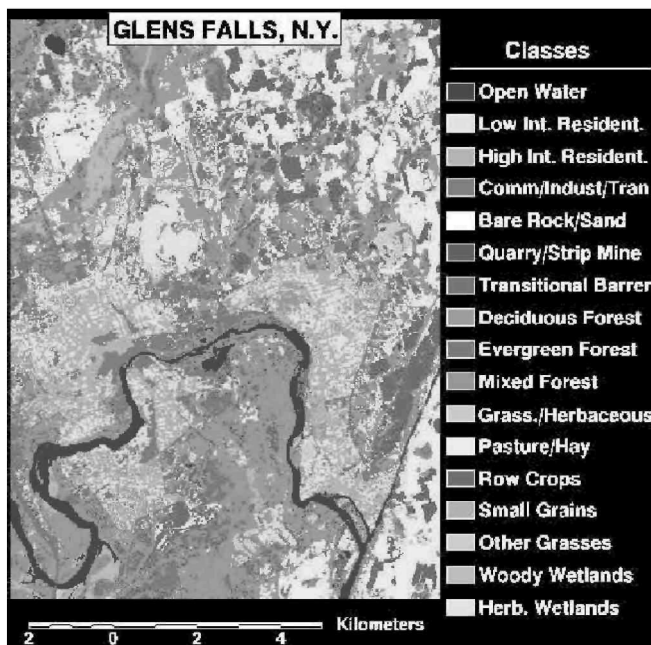


Figure 6-6. Regional Land Cover Characterization as a Raster Database (USGS, 1992).

The third general type of GIS feature is the TIN structure. As the name implies, a TIN structure is composed of a series of irregularly-sized triangular cells. TIN is most frequently used as a mechanism for storing topographical information, though it can also be used to store other discrete or continuous spatial data fields. The applicability of the TIN structure for storing topographical information lies in the simple geometric axiom that three points define a plane, as illustrated in Figure 6-7. As shown, a continuous surface can be represented by a faceted set of triangles with the sides of triangles representing topographical elements such as streams, ridges, and drainage divides (Grayman et al., 1975).

The resolution and accuracy of a TIN database generally depends upon the size of the triangles relative to the degree of detail in the surface being represented. Various mathematical techniques can be used to construct a TIN representation with the most commonly used method for constructing a TIN from a series of points known as Delaunay triangulation (named after a Russian mathematician who invented the procedure in 1934).

Within a GIS, features are organized as separate layers in a manner analogous to the original concept developed by Ian McHarg over 35 years ago. When viewing GIS data, layers can be turned on or off or moved forward or backward in order to better understand or view the spatial relationships.

6.2.2 Topology

An important characteristic of GIS is the concept of topology. Topology may be described as the locational interrelationship between features. Terms such as adjacency, intersection, and connectivity are all topological characteristics that describe how individual features interact. When we look at a map, our eyes and mind construct the topological linkages between features. Observations such as the Mississippi River forming the boundary between Illinois and Missouri, the Monongahela River and Allegheny River intersecting to form the Ohio River, or that a highway intersection between Interstate 95 and Interstate 10 is completely contained within the state of Florida are all statements of topology. GIS

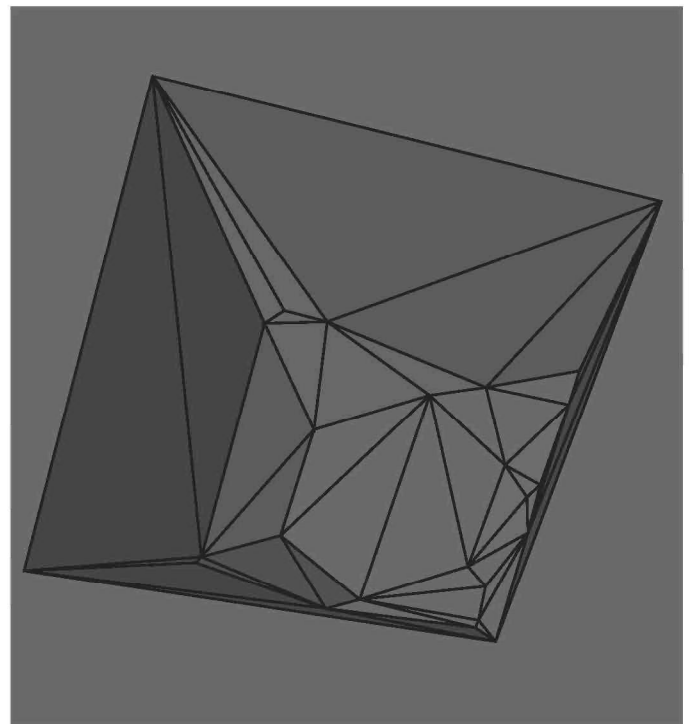


Figure 6-7. Triangulation of Elevation (Z) Data.

constructs the topological relationship between individual features, and this capability is used in various analyses and modeling tasks.

6.2.3 Map Projections, Datum, and Coordinate Systems

Map projections, datum, and coordinate systems provide the mechanism for establishing a unique geographic location for a point on the earth's surface. As scientists have known for centuries (or even millennia), the earth is approximately a spheroid, or in reality, an ellipsoid. However, when we are viewing maps or utilizing spatial data in a GIS, the earth is represented as a planar (flat) system. For maps or plans covering smaller areas, the distortion introduced by ignoring the curvature in the earth's surface is generally insignificant. However, for maps and plans covering larger areas, this distortion would be unacceptable. With the wide availability of regional or national GIS databases, the necessity for accurately determining coordinates is paramount.

The mechanism for converting a location on the earth surface to a flat surface is performed using a map projection. A map projection is a mathematical relationship for performing this conversion. There are many projections or relationships that can be used to make this conversion. Some of the more commonly used projections include:

- State Plane Coordinates (SPC),
- Universal Transverse Mercator (UTM),
- Albers Equal Area,
- Lambert Conformal Conic, and
- Space Oblique Mercator.

In each projection, the earth is divided into a series of zones. A best-fit, separate, planar coordinate system is established for each zone. When examining an area that straddles multiple zones, such as use of the SPC system with a metropolitan area that is in multiple states, coordinate conversions are needed in order to view the entire area in a single, consistent coordinate system.

A final important issue in understanding projections and coordinate systems is the concept of a datum. Because of the complexity of the shape of the earth and the inability to exactly describe it mathematically, the earth has been historically modeled by a best-fit ellipsoid. The parameters of that ellipsoid are defined by key datum points located on or in the earth. For many years, the North American Datum, developed in 1927 (NAD27) that uses a point on the earth's surface in Meade's Ranch, Kansas, as an anchor, was the major standard. Most projections for

North America used this datum.

With improved mathematics and measurements of the earth, the North American Datum of 1983 (NAD83) was developed with a datum located within the earth. This has become the new standard for projections. As a result, a point having a particular coordinate using the NAD27 datum may be shifted by tens or hundreds of feet from a point with the same coordinate using the NAD83 datum. If this is not properly accounted for in a GIS system, a map that used the NAD27 datum would not properly overlay on a map using the NAD83 datum. There are several GIS utilities available that will properly convert datasets from one projection and datum into another, as well as some newer GIS programs that re-project datasets with different coordinate systems "on-the-fly." In either case, it is the responsibility of the GIS user to know the projection and datum associated with each data source and to make the appropriate definition.

6.2.4 GIS Database Design

GIS concepts and software provide an opportunity and a platform for utilizing spatial data. However, in order to effectively store, analyze, and display the data, they must be arranged in an organized manner. Factors that affect database design include: the goals of the GIS implementation, the short- and long-term plans for the GIS, the type and number of users for the particular application, any existing industry-wide standards, and other application-specific factors. Zeiler (1999) discusses the issues associated with database design. Various industry groups are attempting to define generic data structures for a particular industry (such as the water utility industry) in order to facilitate data transfer and common usage of a GIS in that industry (Grise et al., 2000).

6.2.5 Management of GIS

In the early days of GIS development, the GIS was typically developed, managed, and used by a central core of a few people at a governmental or private organization. With the growth and acceptance of GIS, there are now frequently many GIS stations using a specific GIS at an agency, utility or consortium of utilities. Management of such a system and controls on the manner in which changes in the GIS are made are very important issues.

GIS installations may be classified as a personal (or local) system or an enterprise system. In a personal system, the GIS is used and managed by an individual or a small group. On the other hand, an enterprise system may be used by dozens of users distributed throughout an agency and many locations. Though many of the management issues may be similar in these two scales of operation, the enterprise system presents a more challenging situation in terms of

managing the system. Issues such as personnel (user) assignment for changing data or backing up the system and interconnectivity between stations and users must be carefully spelled out in order to insure the integrity of the system.

A common management model for large systems involving multiple users and locations is the combination of a central enterprise GIS with multiple local GIS installations. A central core of managers, who control any modifications to the database and maintain its integrity, maintains the central system. Local stations can either access the enterprise system on a read-only basis or can download copies of all or part of the database for their local use and modification. Specific protocols are then used if changes made at the local level are to be incorporated into the enterprise system. These protocols may include assigned responsibility at the local level to selected layers within the enterprise system. This form of management is relatively common with a county-wide or multi-utility agency managing an enterprise GIS and a water utility maintaining responsibility for the water system layers within the GIS.

6.3 Geospatial Data Management in the Water Industry

Because of the spatial extent and nature of water supply systems, management of geospatial data is an important task. This is accomplished through a series of systems under the overall umbrella of SDMS used to collect, store, and employ these spatial data. In some cases, these various systems are integrated; in other cases, they are independent systems.

6.3.1 CADD

CADD systems have long served as the basis for designing water distribution systems and facilities and for managing maps of the water system. Most utilities and consulting engineers use commercial packages such as AutoCAD, Intergraph or MicroStation. The CADD system may be organized around a collection of maps or plans with a local coordinate system for each plan or may utilize a regional coordinate system such as SPC. Many water utilities use water distribution system models that are integrated with CADD packages.

6.3.2 GIS

GIS has made significant inroads in supplementing or replacing CADD packages at many water utilities. GIS capabilities to store, access and map data are leading to increased usage of GIS in areas such as planning, facilities management, and management of customer and water quality data. Some water utilities share a GIS database with other entities, such as city or county governments, and other utilities, such as gas,

electric, and telephone. At many utilities, GIS technology has also subsumed the capabilities that were formerly classified as AM/FM systems. Similarly, GIS systems may include an LIS as a means of storing land property, parcel, and ownership information and geographic descriptions. DEMs are also a regular feature in GIS packages. They provide a mechanism for storing topographical information. In the past few years, integration of GIS with water distribution system models has been a significant area of research and development in the water industry.

6.3.3 CIS

CIS provides a mechanism for storing and using information on water consumption by customers. The geographic component in a CIS is an address and/or a geographic coordinate. AMR systems facilitate collection of consumption data that can be stored in databases. Standard GIS “address matching” capabilities facilitate conversion of addresses to geographic coordinates. A geographically enabled CIS provides an excellent mechanism for automatically recording current consumption data to be used in water distribution system models.

6.3.4 SCADA

SCADA systems typically include capabilities to remotely access information on the state of the water system, to manually or automatically control components such as pumps and valves, and to store and display current or historical time-series data about system operation. A wide range of commercial SCADA hardware/software systems is available and can be tailored to the specific needs of the water utility. Each component that is referenced in a SCADA system can have a unique geographic identifier that can be used as a linkage to a GIS or other spatial data management systems. Research and development is underway related to integrating SCADA systems and hydraulic/water quality distribution system models so that these models can be used in real-time operation and emergencies.

6.3.5 LIMS

LIMS are computerized systems for managing samples in a laboratory. Such systems typically include a mechanism for storing, managing, displaying, and tracking samples. Since the origin of a sample must be identified both spatially and temporally, this information provides a means of associating LIMS data with other spatial database management systems.

6.3.6 Support Technology

Other technological advances related to spatial database management that are used by water utilities include GPS and RDBMS. GPS is a widely used technology in surveying and can be used for tagging field data with a geographic coordinate. RDBMS is a

general methodology for efficiently storing information as a series of related 2-dimensional tables. Most modern database management systems associated with GIS, LIMS, and other systems utilize the RDBMS structure.

6.4 Integration of Geospatial Data Management and Modeling

The concept of integrating water distribution system modeling with geospatial database management systems has been evolving over the past quarter of a century and continues to be a major focus of development in the water industry today. Early water distribution system models were stand-alone entities. In the very early models, input was provided by punch cards and output was in the form of printed tabular information. This cumbersome I/O gave way to input via terminals in the 1980s and GUIs in the 1990s. The 1990s also saw the first commercial integration of water distribution system models with CADD followed by integration with GIS in the 2000s.

The basis for integrating water distribution system models with geospatial data can be traced back to an early study that interfaced a planning level sewer design model with a TIN-based GIS called ADAPT (Areal Design And Planning Tool) (Grayman et. al., 1975). This approach was called “geo-based modeling” and was subsequently applied to various other water engineering situations such as hydrologic modeling (Males and Gates, 1979). In these systems, a geo-based network representing sewer lines or streams was integrated with GIS elevation, land use, and soil data. This network directly interfaced with design and simulation models.

In the 1980s, the same geo-based modeling concept was applied to water distribution system analysis through a series of EPA research projects. The Water Supply Simulation Model (WSSM) integrated a geo-based, link-node system to several models including a hydraulic model, a steady-state water quality and cost allocation model, and various display and editing routines (Clark and Males, 1985). Subsequently, WSSM was expanded to include an interface to GIS files using AutoCAD. USGS digital line graph (DLG) files of road networks and DEMs were used within AutoCAD to create a detailed representation of the water distribution system. The resulting database was used to generate an input file for the Wadiso hydraulic model whose engine worked as a prototype for EPANET.

In the past 10 years, commercial vendors of network modeling software working in conjunction with CADD and GIS vendors have led the integration of

modeling software and spatial database technology. In the mid 1990s, hydraulic/water quality models were built to operate within AutoCAD. More recently, commercial modeling systems have been released as a version that are fully integrated and operate within the GIS environment. Commercial products include WaterGEMS (Haestad Methods/Bentley Systems) and InfoWater (MWHSoft).

6.4.1 Model Integration Taxonomy

The term “integration” can refer to a wide range of capabilities related to use of network models in conjunction with a spatial database system. Shamsi (2001) provides a taxonomy of three levels for model-database integration. These are described as interchange, interface, and integration.

Interchange provides a mechanism for transferring data between a spatial database such as GIS and a model. With interchange, there is no direct linkage between the two systems. Rather, they are run separately and information is extracted from one system and stored in an intermediate file that is subsequently accessed by the other system. In the direction of database to model, information stored in a GIS is used to generate a complete or partial dataset that is used as input to the model. In the other direction, output from a model is used as input into a GIS in order to display the results of the model application. Most commercial water distribution modeling packages can interchange data with CADD and GIS platforms.

An interface involves a direct connection between the database and the model in order to transfer information in either direction. As is the case in interchange, the two systems still operate independently, but in this case, there is a direct linkage so that intermediate files are not necessary. Protocols and structures must be established and compatible within the two systems in order to support this interface. Current trends are directed towards open architecture in which information on the data structures for models and GIS are designed to data structures. For example, H2OMap and WaterCAD are standalone software packages which can directly interface with data in CADD and GIS platforms.

True integration is the most sophisticated of the three methods. Ideally, the two systems work together seamlessly as a single entity. In such integration, either the model can operate within the spatial database software or the spatial database capability can be part of the model. For example, WaterCAD and H2ONET software packages are integrated and operate within AutoCAD. InfoWater and WaterGEMS software packages are integrated to operate within ArcGIS.

6.4.2 Issues in Integrating GIS and Water Distribution System Models

As an evolving technology, there are still issues in truly integrating GIS technology with water distribution system models. These issues primarily revolve around the level of detail required in the two systems and the procedures for updating the model and the database.

In most cases, a water utility GIS is used for many purposes including mapping, facility management, planning, and modeling support. As a result, there may be a great deal of detail in the GIS. For example, it may include hydrants, shutoff valves, water meters and household connections, air release valves, and other appurtenances. On the other hand, typically, water distribution system models do not explicitly include many of these components. This is shown graphically in Figure 6-8. In this case, only junction nodes and pipes are included in the model representation. As a result, the GIS representation includes 17 links and 11 nodes, and the model representation includes 6 links and 3 nodes. The disparity between the two representations can increase by another order of magnitude if water meters and customer connections are included in the GIS. Various approaches are taken to deal with this situation.

- A very detailed model is constructed that includes all of the elements in the GIS. This solution can result in a very large model with an excessive number of nodes and links.
- The GIS representation goes through a consolidation (skeletonization) procedure to eliminate unneeded nodes and to aggregate the resulting links in order to construct the model representation. Though this results in a more appropriate model, it adds an intermediate step between the GIS and the model. Additionally, after the consolidation process, there is no longer a one-to-one correspondence between GIS and model features. This lack of correspondence leads to issues related to storing model output in the GIS and updating the model.
- Multiple representations are maintained within the GIS for different uses. The detailed representation is the complete, base case and used for facility management while the skeletonized version is used for modeling. This approach has the limitation that requires changes in information to be made in multiple databases.
- The basic link-node network (as used in the model) is maintained as the base case in the GIS and associates other components (such as hydrants) with links rather than structurally embedding them in the network.

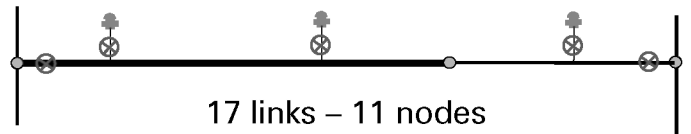


Figure 6-8a. Typical Representation of a Pipe Section in GIS.

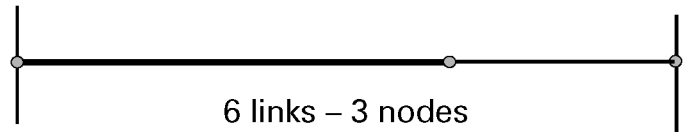


Figure 6-8b. Typical Representation of a Pipe Section in a Network Model.

In any of the options described above, procedures for updating the GIS are essential. There are many issues associated with GIS updating such as authorization of specific users to make changes, nature of the changes as permanent or part of a 'what-if' modeling scenario, and frequency of replication of the two databases if separate model and GIS files are maintained. All of these should be carefully spelled out prior to designing and implementing a GIS.

6.5 Use of GIS in Water Utilities - Case Studies

This section presents the potential uses of GIS in the water utility industry. Case studies from the Las Vegas Valley Water District (LVVWD) and Denver Water are presented.

6.5.1 Use of GIS at LVVWD

Between 1989 and 2004, Las Vegas grew faster than any other metropolitan area in the U.S. As a result, LVVWD has more than doubled its service area population during this period. In 1989, the service area population was 558,000 and in 2004 it rose to 1,209,000, representing an increase of 651,000 people serviced by LVVWD (Jacobsen and Kamojjala, 2005). Figure 6-9 is a GIS representation of the LVVWD distribution system growth between 1989 and 2004.

To address a variety of issues related to this rapid growth, LVVWD integrated the functions of master planning, operational planning, and development review by integrating its GIS data with modeling, SCADA, and enterprise data (such as CIS, AM/FM and LIMS). Figure 6-10 presents the conceptual relationship model of these functions and potential integration benefits (Jacobsen et al., 2005).

During the process of integration, LVVWD developed a one-to-one relationship between the GIS spatial data and its network model (Jacobsen and Kamojjala, 2005). An example of this one-to-one relationship is

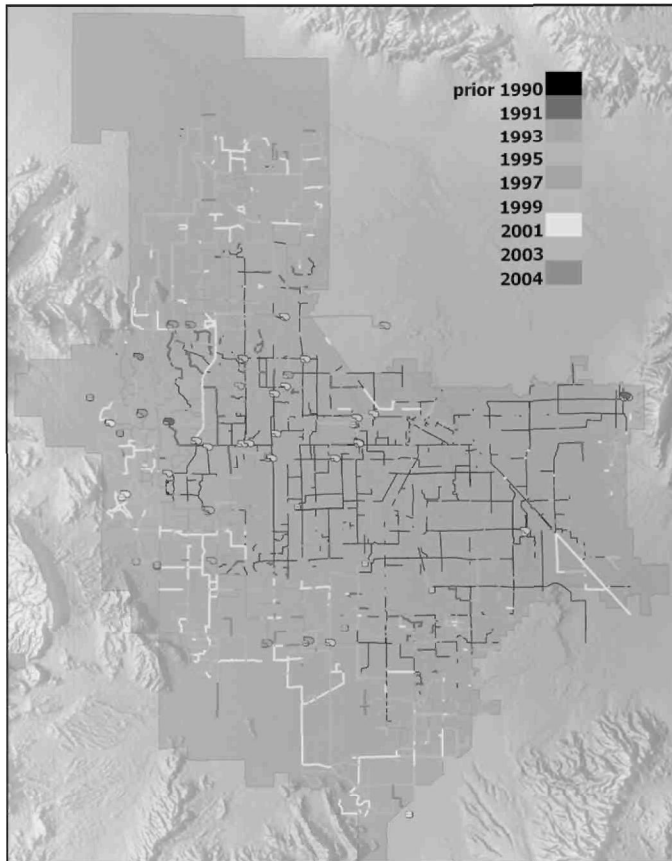


Figure 6-9. LVVWD Distribution System Growth.

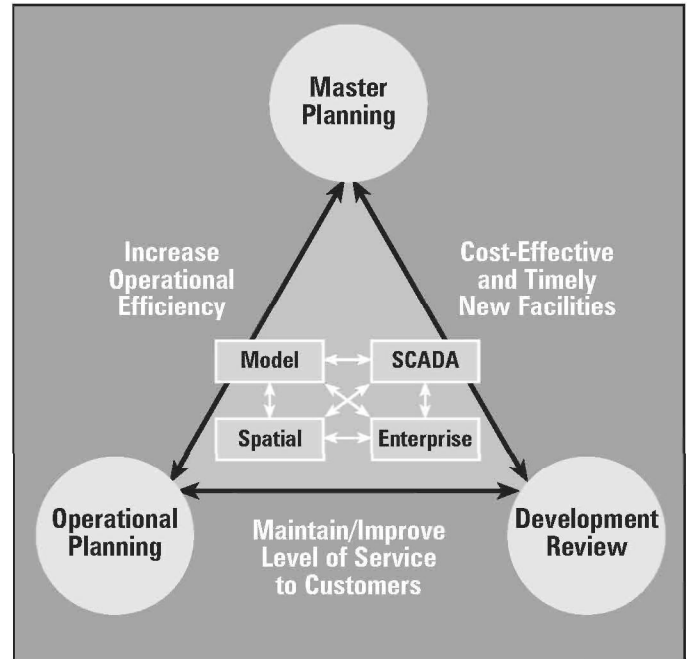


Figure 6-10. Conceptual Relationship Model for Integration.

shown in Figure 6-11. Depending on the size of the network, developing such a relationship and subsequent data integration has both advantages and disadvantages.

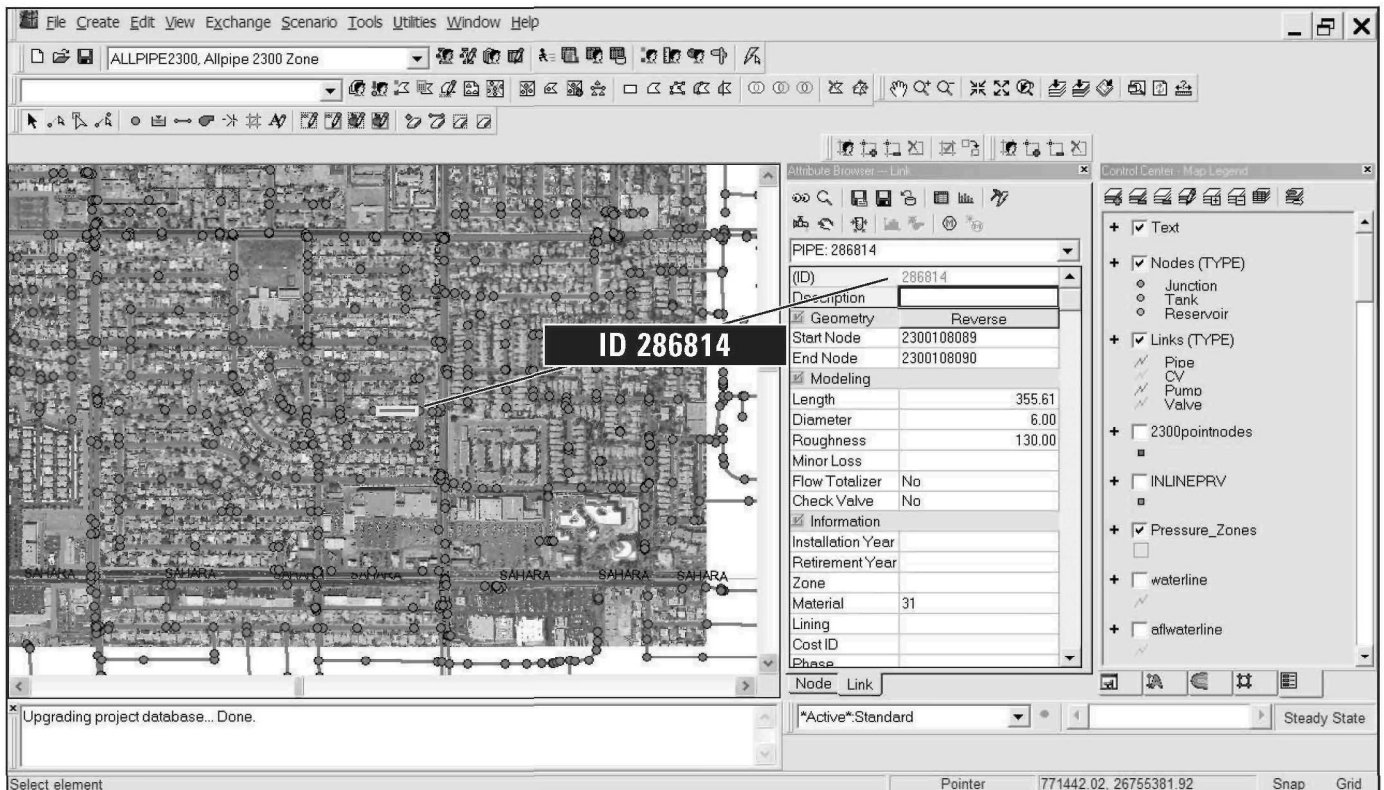


Figure 6-11. One-to-One Relationship Between GIS and Network Modeling Data.

The advantages include ease of search and retrieval with other data/applications, and ease of importation, development, and maintenance. For a large network model, the disadvantages include an increase in the runtime of the network model due to the addition of detailed components and relatively slow water quality simulations. To minimize this, LVVWD has taken an “all-pipes capable” approach where the distribution system is divided according to existing pressure zones and attached to an operational backbone network (skeletonized). Each of the zone models can be attached seamlessly to the backbone network for detailed hydraulic and water quality modeling. Examples of how GIS data are used by LVVWD on a day-to-day basis are presented below.

6.5.1.1 Pressure Complaint Resolution

Once a pressure complaint is received from a customer, the GIS data is searched for parcel and account information, together with modeled and measured pressure data in the vicinity of the complaint. Figure 6-12 shows an example search window. Depending on the results of the analyses, a crew may be dispatched to trace field pressures and abnormal conditions from the water supply source to the customer location, and to install hydrant pressure recorders to capture dynamic variations. Upon retrieval of field information, model and field results are compared to identify possible problems. Figures 6-13 and 6-14 present

examples resulting from this search (Jacobsen and Kamojjala, 2005).

6.5.1.2 Water Main Break Analysis

During a water main break, it is critical to quickly identify the distribution system valves that must be closed in order to minimize water loss, potential flooding, or possible contamination. Repairs must be performed quickly so that service can be resumed. Figure 6-15 illustrates the procedure for rapidly identifying the valves to be isolated utilizing the GIS and modeling tools. A list of affected customers is generated for appropriate notification (Figure 6-16). An analysis is performed to evaluate the impact on existing services. Figure 6-17 shows a comparison of pressures after a shutdown and identifies a lower-pressure area after the shutdown. Response to emergencies, such as main breaks, can be provided quickly and accurately using integrated GIS tools (Jacobsen and Kamojjala, 2005).

6.5.2 Geo-coding for Demand Forecasting and Allocation at Denver Water

Between January 1997 and December 2000, Denver Water conducted a treated water study to evaluate the transmission, pumping and storage system for capacity and the need for new facilities for capital planning and operations. Denver Water made extensive use of GIS tools for demand forecasting and

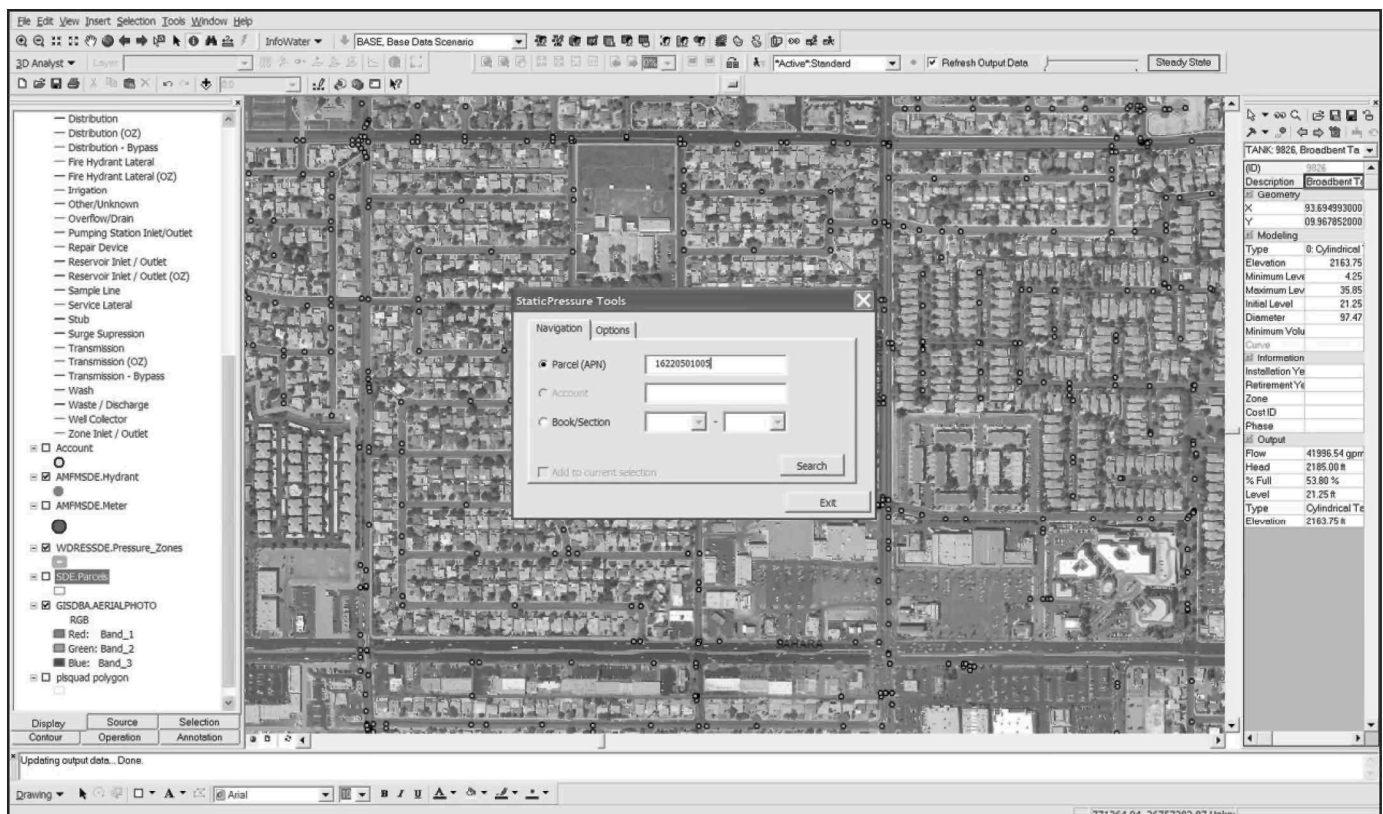


Figure 6-12. Pressure Complaint Resolution – GIS Parcel/Account Search Window.

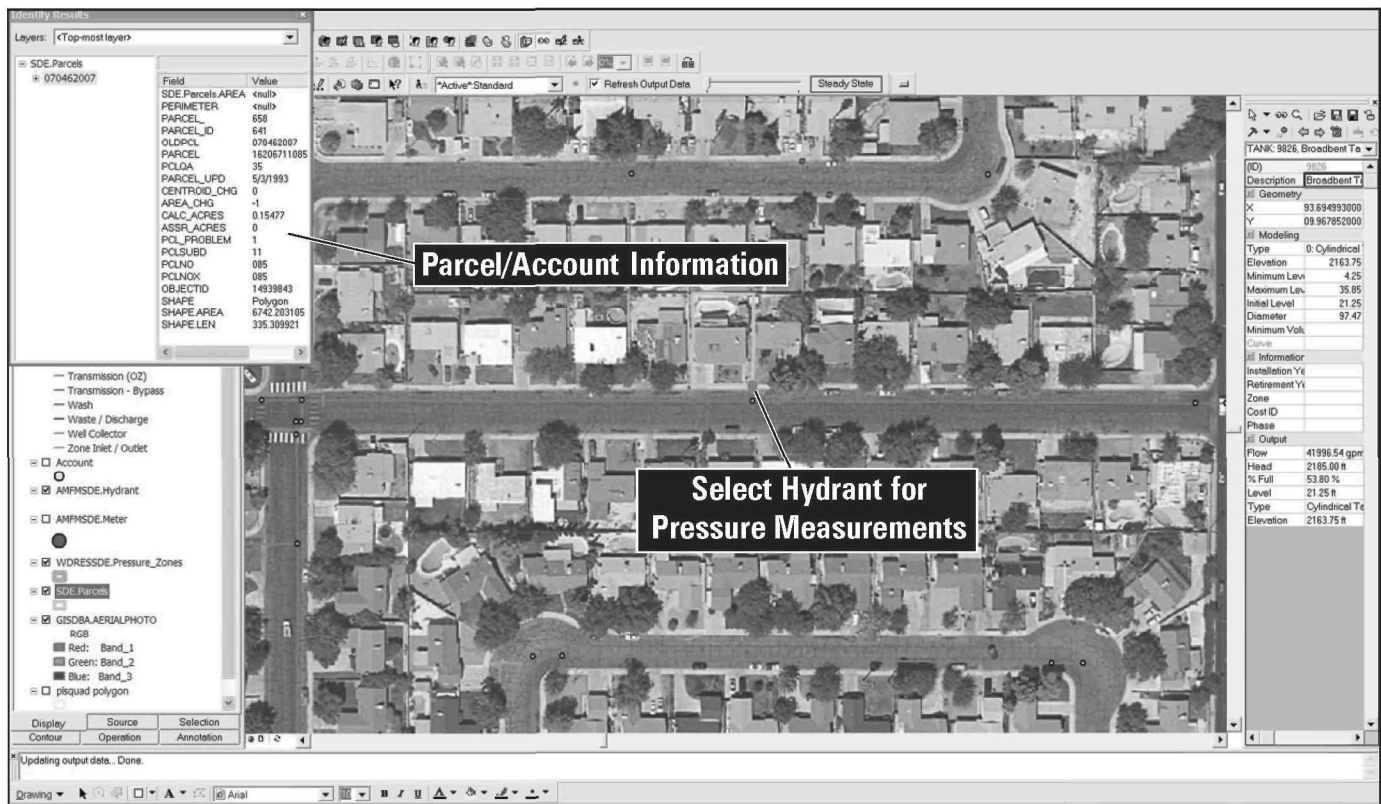


Figure 6-13. Pressure Complaint Resolution – Parcel and Hydrant Location.

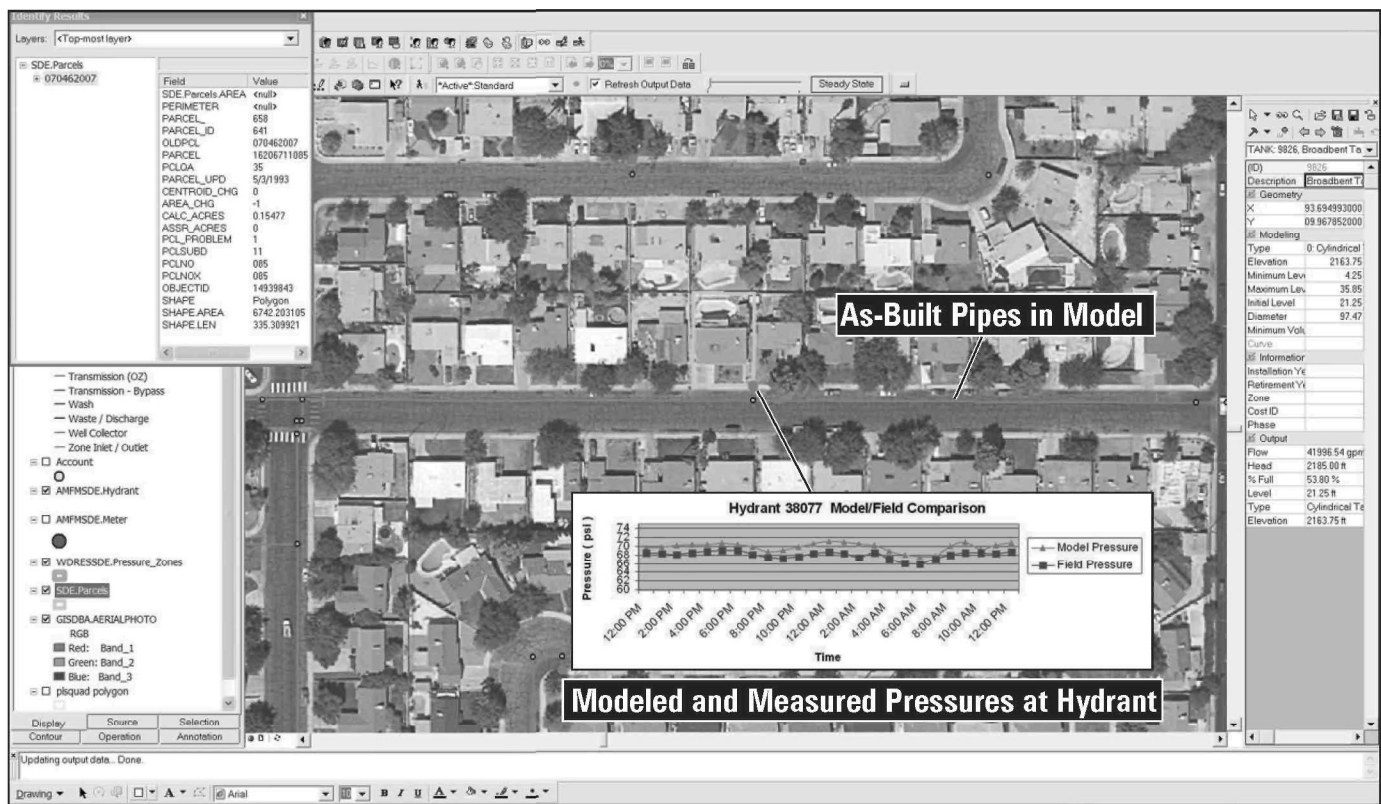


Figure 6-14. Pressure Complaint Resolution – Model and Field Pressure Comparison.

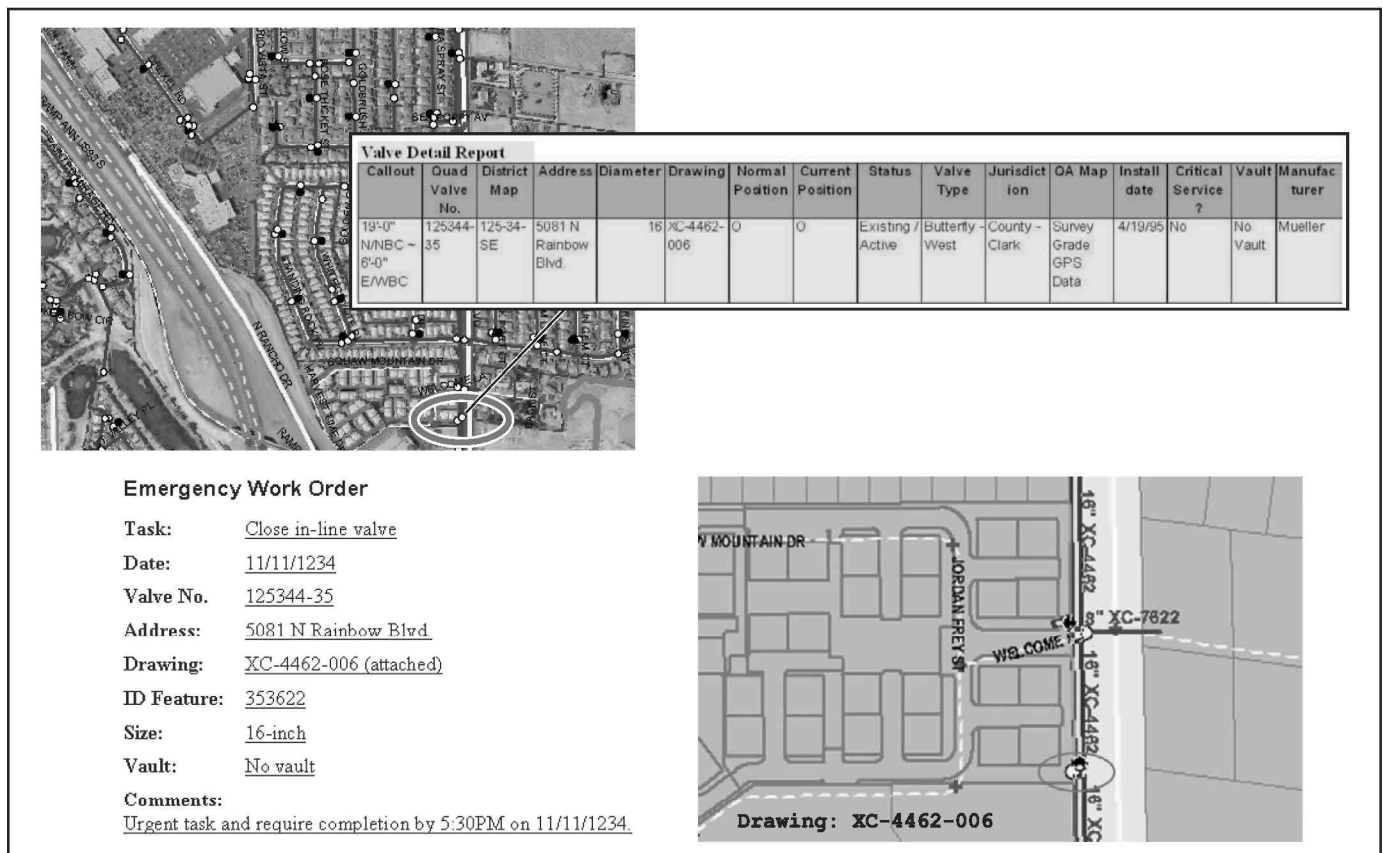


Figure 6-15. Water Main Break Analysis – Valve Isolation.

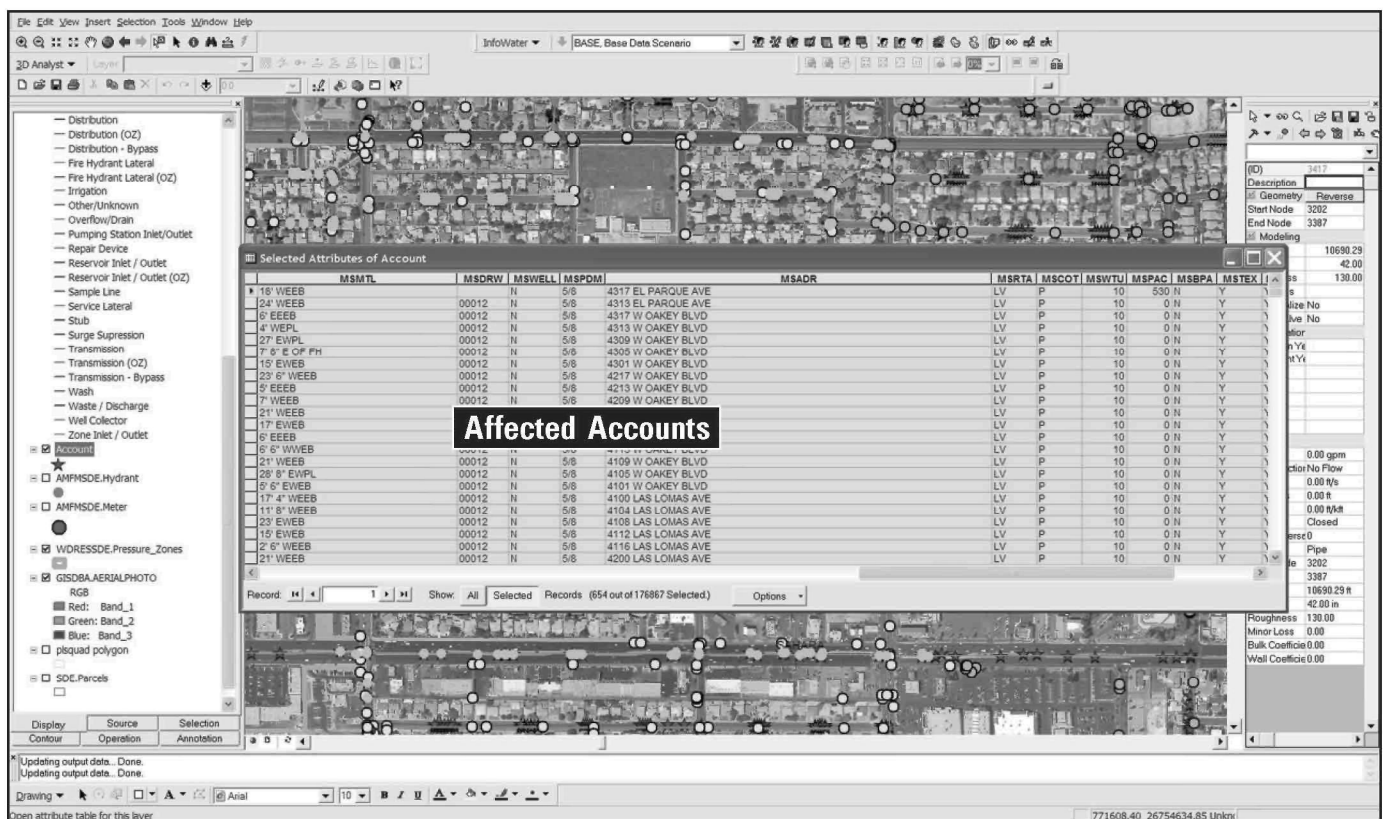


Figure 6-16. Water Main Break Analysis – Impacted Customer List.



Figure 6-17. Water Main Break Analysis – Comparison of Junction Pressures - Before and After Shutdown.

allocation as part of this analysis. Specifically, existing demands were spatially allocated using address geo-coding (Strasser et al., 2000).

Denver Water has been a completely metered system since 1992. Historic consumption data is available from 1993 to the present. Consumption data was extracted from the billing system, and imported into an MS Access database for use in various tasks including the treated water study. The extracted data included both customer address and customer class information (e.g., single family, multi-family, commercial, industrial, and public). The customer class information allowed the demand information to be aggregated by customer class. Because the service area was large (over 250 square miles), it was important to identify the location of the consumption demand points. This is where the use of GIS became very important (Strasser et al., 2000).

Denver Water used the “address geo-coding” feature available within ArcInfo which allowed for each customer or demand point to be identified on a base map. Using this process, a dot is placed on the base map representing each customer that could be positively geo-coded. The match rate was over 93 percent. Those accounts that could not be geo-coded, mostly large accounts representing master meter accounts, and wholesale customers, were entered in the system manually. Results from the geo-coding process for one pressure zone are illustrated in Figure 6-18. A quality control check was performed on the results of this geo-coding process by reconciling consumer demands with Denver Water’s annual statistical report (Strasser et al., 2000).

6.6 Summary

Use and management of geospatial data is an important aspect of the design and operation of water systems. This can be accomplished through a range of systems under the overall umbrella of SDMS utilized to collect, store, and use the spatial data. This umbrella covers not only the broad topics of GIS and CADD that are widely recognized as geospatial data systems, but also systems such as SCADA and LIMS that have a spatial component associated with all data.

The area of spatial database management is continuing to evolve within the water industry. Just as the capabilities of the various individual components within the SDMS umbrella continue to expand, the integration of the various systems is an active area of development. Water distribution system analysis is a significant beneficiary of these improvements and integration. As a result, models can be built more quickly and in greater detail. Information on facilities and demands can be routinely updated. The results of a model application can be rapidly displayed and viewed along with other spatial data. The prospect of real-time application of models to assist in system operation under routine conditions or under emergency conditions is getting closer.

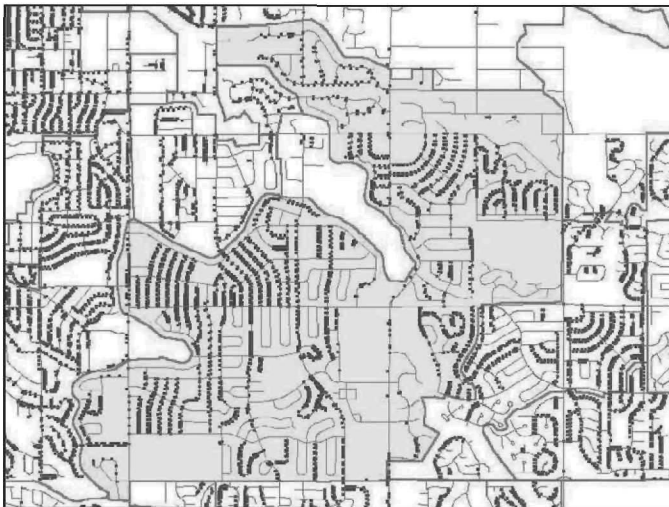


Figure 6-18. GIS Geo-coding - Metered Sales Demand Allocation Procedure.

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Chapter 7

Real-World Applications – Planning, Analysis, and Modeling Case Studies

The previous chapters of this reference guide showcased several tools for analyzing water quality in drinking water distribution systems. Some of these chapters also have relevant case studies that relate to the individual topic of discussion for that chapter. This chapter focuses on the broader application of multiple tools to analyze real-world situations. The types of applications presented here include: reconstruction of historical contamination events, analysis of waterborne outbreaks of infectious diseases, regulatory compliance, monitoring systems location, and security. Each real-world application is presented as an individual case study and the portions related to water quality and analysis have been highlighted along with some specifics on techniques used in the analysis.

7.1 Analysis of Waterborne Outbreak – Gideon, Missouri

This case study is focused on evaluating the distribution of microbiologically contaminated water in a distribution system. The supporting investigations for this case study were primarily sponsored by the EPA, CDC, and the State of Missouri.

Key Phrases to Characterize Case Study: water borne outbreak analysis, *salmonella*, tank contamination, hydraulic and water quality modeling, exposure modeling, contamination assessment, and flushing.

7.1.1 Gideon Case Study Overview

From November 1993 through January 1994, the Missouri Department of Health (MDOH) had identified 31 cases of laboratory-confirmed salmonellosis infections associated with a waterborne outbreak in Gideon, Missouri (Clark et al., 1996). The State Public Health Laboratories identified 21 of these isolates as dulcitol negative *Salmonella* serovar *Typhimurium*. *Salmonella* is a pathogenic bacterium that has been classified into several serotypes (common set of antigens). *Salmonella* serovar *Typhimurium* is among the most common *Salmonella* serovars causing salmonellosis in the U. S. Fifteen of the 31 laboratory culture-confirmed patients were hospitalized (including two patients hospitalized for other causes and who developed diarrhea while in the hospital). These 15 patients were admitted to 10 different hospitals. Seven nursing home residents exhibiting diarrheal illness died; four of these patients were culture confirmed (the other three were not cultured). Two of the patients had positive blood

cultures. Interviews conducted by the MDOH during this period suggested that there were no food exposures common to a majority of the patients. However, all of the ill persons, including the culture-confirmed patients, had consumed municipal water which supported the association. The MDOH reported their suspicion to the Missouri Department of Natural Resources (MDNR).

7.1.2 The Gideon Water System Setup

The Gideon municipal water system was originally constructed in the mid-1930s and obtained water from two adjacent, 1,300 ft deep wells. The well waters were not disinfected at the time of the outbreak. After the outbreak emergency, chlorination was initiated, and later a permanent chlorination system was installed. The distribution system consisted primarily of small-diameter (2-, 4-, and 6-inch) unlined, steel and cast iron pipe. Tuberculation and corrosion were major problems in the distribution pipes. Raw water temperatures were unusually high for a groundwater supply system (58°F), because the system overlies a geologically active fault. Under low flow or static conditions, the water pressure was close to 50 psi. However, under high flow or flushing conditions the pressure dropped dramatically. These sharp pressure drops were evidence of major problems in the Gideon distribution system. The municipal system had two elevated tanks. One tank was a 50,000 gallon (gal) tank (referred to as small tank) and the other was a 100,000 gal tank (referred to as large tank).

Initially, another 100,000 gal privately owned tank was suspected to be the cause of the outbreak (as it was in a state of disrepair) and connected to the city water system. However, subsequent investigations revealed that this private tank was connected via a backflow prevention valve to the city water system that was later confirmed to be functional. Furthermore, the *Salmonella* found in a sample collected at a hydrant matched the serovar of the patient isolate when analyzed by the CDC laboratory (comparing deoxyribonucleic acid [DNA] fragments using pulse field gel electrophoresis). Although the samples from the private tank sediment also contained *Salmonella* serovar *Typhimurium* dulcitol negative organisms, the isolate did not provide an exact DNA match with the other two isolates. No *Salmonella* isolates were found elsewhere in the system. Therefore, the subsequent EPA field investigations and modeling efforts focused on the two municipal tanks as the source of contamination.

7.1.3 EPA Field Study

On January 14, 1994, an EPA field team, in conjunction with the CDC and the State of Missouri, initiated a field investigation that included a sanitary survey and microbiological analyses of samples collected on site. A system evaluation was also conducted in which EPANET was used to develop various scenarios to explain possible contaminant transport in the Gideon system. Prior to the Gideon outbreak, a similar waterborne disease outbreak in Cabool, Missouri, and subsequent advancements in water quality modeling firmly established the use of water quality models to analyze such events.

The key analysis was focused on a flushing program conducted earlier by the utility in response to taste and odor complaints. A sequential flushing program was conducted on November 10, 1993, involving all 50 hydrants in the system. The flushing program was started in the morning and continued through the entire day. Each hydrant was flushed for 15 minutes at an approximate rate of 750 gallons per minute (gpm). It was observed that the pump at one of the wells was operating at full capacity during the flushing program (approximately 12 hours), which would indicate that the municipal tanks were discharging during this period.

During the evaluation, it was hypothesized that the taste and odor problems may have resulted from a thermal inversion that had taken place due to a sharp temperature drop prior to the day of the complaint. If stagnant or contaminated water were floating on the top of a tank, a thermal inversion could have caused this water to be mixed throughout the tank and to be discharged into the system resulting in taste and odor complaints (Fennel et al., 1974). As a consequence, the utility initiated the aforementioned city-wide flushing program. Turbulence in the tank from the flushing program could have stirred up the tank sediments that were subsequently transported into the distribution system. It is likely that the bulk water and/or the sediments were contaminated with *Salmonella* serovar *Typhimurium*. During the EPA field visit, a large number of pigeons (bird droppings are known to contain *Salmonella*) were observed roosting on the roof of the 100,000 gal municipal tank.

7.1.4 Distribution System Evaluation

The EPA study team evaluated the effects of distribution system design and operation, demand, and hydraulic characteristics on the possible propagation of contaminants in the system. Given the evidence from the lab samples and the results from the valve inspection of the private tank, it was concluded that the most likely contamination source was bird droppings in the large municipal tank. Therefore, the analysis concentrated on propagation of water from

In 1991, a joint workshop sponsored by the EPA and AwwaRF recommended the application of water quality modeling techniques to evaluate waterborne disease outbreaks. The first opportunity to attempt this type of application arose as a result of an outbreak that occurred between December 15, 1989, and January 20, 1990, in Cabool, Missouri, population 2,090 (Geldreich et al., 1992). During the outbreak, residents and visitors to Cabool experienced 243 cases of diarrhea (85 bloody) and six deaths. The illness and deaths were attributed to the pathogenic agent *E. coli* serotype O157:H7. At the time of the outbreak, the water source was untreated groundwater. Shortly after the outbreak was identified, EPA was invited to send a team to conduct a research study with the goal of determining the underlying cause of the outbreak.

Exceptionally cold weather prior to the outbreak contributed to two major water system line breaks and 43 water meter replacements throughout the city area. The sewage collection lines in Cabool were located (for the most part) away from the drinking water distribution lines but did cross or were near to water lines in several locations. At the time of the outbreak, stormwater drained via open ditches along the sides of the streets and roads. During heavy rainfalls, sewage was observed to overflow manhole covers, and to overflow streets in several locations, parking lots and residential foundations.

The Dynamic Water Quality Model (DWQM), developed by EPA, was applied to examine the movement of water and contaminants in the system (Grayman et al., 1988). Steady-state scenarios were examined, and a dynamic analysis of the movement of water and contaminants associated with meter replacement and the line breaks was conducted. Typical demand patterns were developed from available meter usage for each service connection, and it was found that the water demand was 65 percent of the average well production, indicating inaccurate meters, un-metered uses, and a high water loss in the system.

The modeling effort revealed the pattern of illness occurrence was consistent with water movement patterns in the distribution system assuming two water line breaks. It was concluded that some disturbance in the system, possibly the two line breaks or 43 meter replacements, allowed contamination to enter the water system. Analysis showed the simulated contaminant movement covered 85 percent of the infected population.

The application of DWQM proved to be a vital step in completing the analysis of the outbreak. The next opportunity to apply water modeling techniques occurred in 1994 as a result of a waterborne outbreak in Gideon, Missouri (Clark et al., 1996). In the intervening period, EPA had developed EPANET and Gideon provided an opportunity to test its application.

the large municipal tank in conjunction with the flushing program. Other possible sources of contamination, such as cross connections were also studied.

The system layout, demand information, pump characteristic curves, tank geometry, flushing program, and other information needed for the modeling effort were obtained from maps and demographic information and numerous discussions with consulting engineers and city and MDNR officials. EPANET was used to conduct the contaminant propagation study (Rossman et al., 1994).

The EPANET network model was calibrated by simulating flushing at the hydrants assuming a discharge of 750 gpm for 15 minutes. The “C” factors (pipe roughness – see Chapter 4) were adjusted until the head loss in the model matched head losses observed in the field. After the calibration, the hydraulic model was simulated for 48 hours. Thereafter, the flushing program was simulated starting at 8 a.m. on day 3, by sequentially imposing a 750 gpm demand on each hydrant for 15 minutes. Utilizing the TRACE option in EPANET, the percentages of water from both municipal tanks were calculated at each node over a period of 72 hours.

During the simulation of the flushing program, the pump at one of the wells was operated (as previously observed) at full capacity, which was over 800 gpm, and then reverted to cyclic operation. The simulation results showed that the tank elevation fluctuated for both municipal tanks, and both the tanks discharged during the flushing program. At the end of the flushing period, nearly 25 percent of the water from the large municipal tank passed through the small municipal tank where it was again discharged into the system. The model predicted dramatic pressure drops during the flushing program. Based on the information available, it was felt that these modeling results replicated the conditions that existed during the flushing program closely enough to provide a basis for an analysis of water movement in the system.

Data from the simulation study, the microbiological surveillance data, and the outbreak data were utilized to provide insight into the nature of both general contamination problems in the system and the outbreak itself. The water movement patterns showed the majority of the collected samples that were total coliform and fecal coliform (FC)-positive occurred at points within the zone of influence of the small and large tanks. During both the flushing program and for large parts of normal operation, these areas were predominately served by tank water, which confirmed the belief that the tanks are the source of the fecal contamination since there were positive FC samples

prior to chlorination. Figure 7-1 shows the comparison of early confirmed cases of *Salmonella* positive sample versus the estimated distribution of tank water during the first six hours of the flushing program.

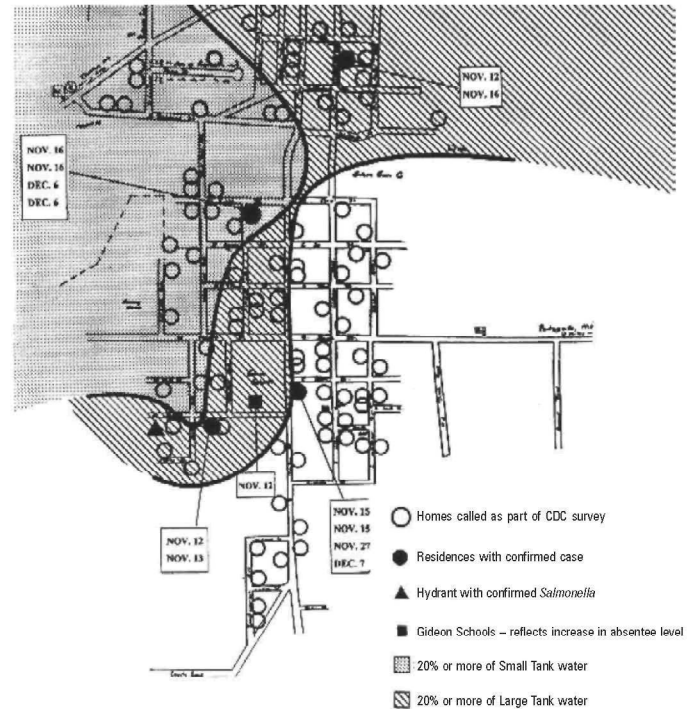


Figure 7-1. Comparison of Early Confirmed Cases of *Salmonella* Positive Sample Versus the Estimated Distribution of Tank Water During the First 6 Hours of the Flushing Program.

7.1.5 Case Study Summary and Conclusions

Data from the CDC survey of the outbreak, in combination with the EPANET simulated water movement, were utilized to establish the possible source of contamination. An overlay of the CDC data on the water movement simulations showed that the areas served by the small and large tanks (during the first six hours of the flushing period) coincided with the earliest recorded infectious cases. Furthermore, the earliest recorded cases and the positive *Salmonella* hydrant sample were found in the area that was primarily served by the large tank, but outside the small tank's area of influence.

The investigators concluded that during the first six hours of the flushing period, the water that reached an infected resident and the Gideon School (the earliest reported infections) was almost totally from the large tank. Based on the results of the study, it appeared that the contamination had been occurring over a

period of time, which is consistent with the possibility of bird contamination. It is likely that the contaminant was pulled through the system during the flushing program. The application of EPANET to the outbreak proved to be a vital part of the study.

7.2 Reconstructing Historical Contamination Events - Dover Township (Toms River), NJ

This case study is focused on evaluating the distribution of chemically contaminated source water in a distribution system. The supporting investigations for this case study were primarily sponsored by the ATSDR. The investigations involved several other organizations. The major contributors included the New Jersey Department of Health and Senior Services (NJDHSS), the Multimedia Environmental Simulations Laboratory at the Georgia Institute of Technology, EPA's National Risk Management Research Laboratory, and the U.S. Geological Survey.

Key Phrases to Characterize Case Study: historical reconstruction, hydraulic and water quality modeling, exposure modeling, contamination assessment, source tracing, source contribution, model calibration, sensitivity analysis, genetic algorithm.

7.2.1 Case Study Overview

In August 1995, responding to an evaluation requested by the ATSDR, the New Jersey Department of Health (now NJDHSS) determined that the childhood cancer incidence rate in Dover Township (and the Toms River section) was higher than expected for all malignant cancers combined (brain and central nervous system cancer, and leukemia, Berry, 1995). In March 1996, NJDHSS and ATSDR developed a Public Health Response Plan (PHRP) describing actions these agencies would take to investigate the unexpected increase in childhood cancers and environmental concerns in Dover Township (NJDHSS and ATSDR, 1996). The PHRP included a list of several evaluations. One of the key evaluations was to identify potential environmental exposure pathways relative to two National Priorities List (NPL) sites in Dover Township (Figure 7-2) – Ciba-Geigy and Reich Farm. Figure 7-2 also shows the two public water supply well fields (Parkway and Holly) that were identified as potential routes of exposure. These well fields are not only located in the vicinity of the aforementioned NPL sites, but are also in areas where the statistically higher childhood cancer rates were established.

The ensuing evaluations revealed the presence of a previously unidentified compound, styrene acrylonitrile (SAN), in the groundwater from the Parkway well field that could be traced to the Reich Farm NPL site.

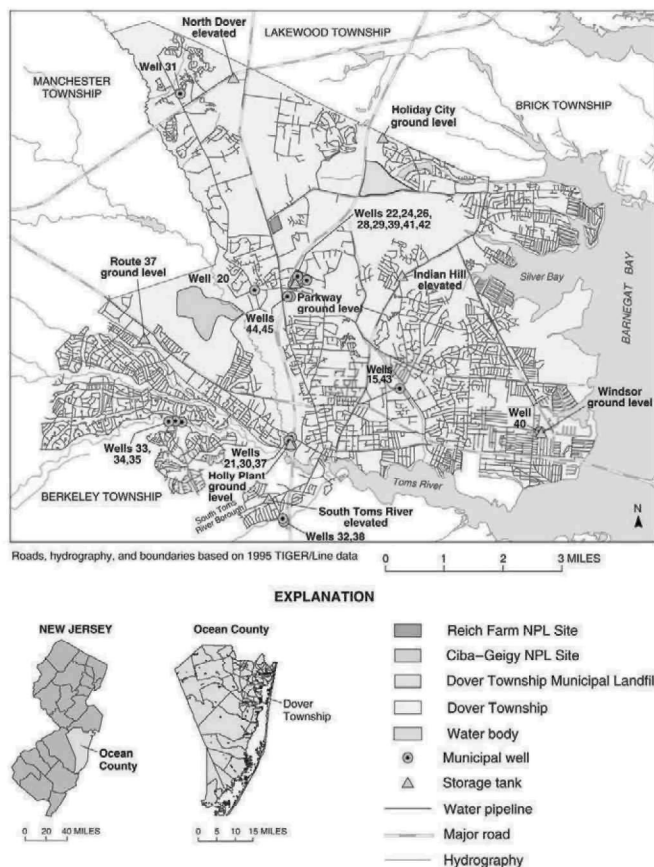


Figure 7-2. Investigation Area, Dover Township, Ocean County, NJ (modified from Maslia et al., 2001).

Similarly, a search of historical records revealed contamination (primarily semivolatile organics [SVOCs]) of the Holly well fields that could be traced to the Ciba-Geigy NPL site. Furthermore, one of the hypotheses for the epidemiologic case-control study was that the higher cancer incident rate was related to the higher exposure to public water supplies with documented contamination (the Parkway and Holly well fields). To assist NJDHSS with the contaminated drinking water exposure assessment component of the epidemiologic study, ATSDR developed a water distribution model for the study area using the EPANET software. This network model was used to simulate historical characteristics of the water distribution system serving Dover Township from 1962–1996. Because there was a lack of historical contaminant-specific data during most of the period relevant to the epidemiologic study, the modeling effort focused on estimating the percentage of water that a study subject might have received from each well that supplied water to the impacted area. The following subsections present a brief overview of the water distribution modeling effort (both hydraulic and water quality) followed by a summary of findings and conclusions.

Prior to the ATSDR's analysis of well field contamination in Dover Township and the potential linkages to childhood diseases, another study in Woburn, Massachusetts, heralded the era of such analyses. Though both the model and graphical presentations are primitive by today's standards, they were effective in providing a quantitative basis for assessing the spread of contaminants in the distribution system. The following is a brief description of the Woburn analysis.

In May 1979, the Massachusetts Department of Environmental Quality Engineering discovered that two wells (Wells G & H in the B Zone – See Figure 7-3) in Woburn, Massachusetts were contaminated with toxic chemicals. Subsequent analysis showed that parts of the city experienced elevated levels of childhood leukemia and other illnesses attributed to drinking water derived from these wells. This event resulted in legal action, a diverse set of scientific studies that are still ongoing, and the publication of a book entitled *A Civil Action* (Harr, 1995). Early steady-state distribution system hydraulic and water quality models were also used as a means to track the movement of the contaminated water in the distribution system under a range of operating and demand conditions (Murphy, 1986). The accompanying figure is one example of a plot resulting from this early modeling effort. As shown in Figure 7-3, based on the modeling, the city was divided into three zones for each scenario – the A zone that received no water from the contaminated wells, the B zone that received all of its water from the contaminated wells, and the C zone that received some of its water from the contaminated wells.

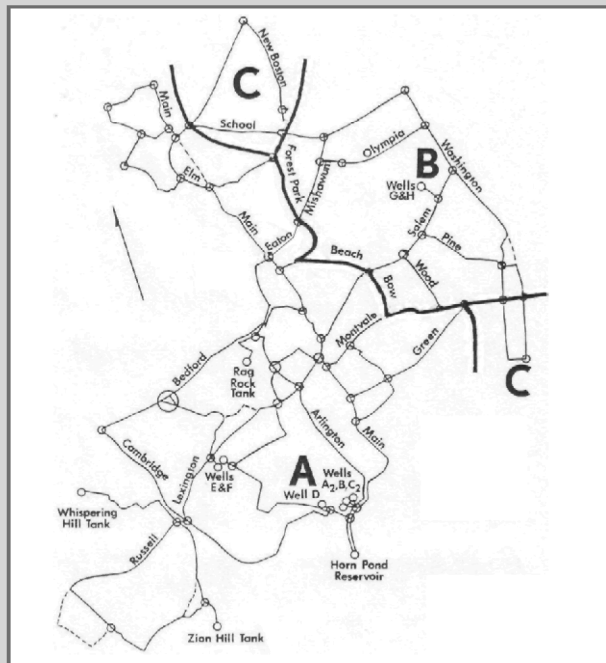


Figure 7-3. Distribution System Zones – Woburn, MA (May 1969).

7.2.2 Overall Modeling Approach

Because of the lack of historical hydraulic and water quality information, the water distribution system was characterized using data gathered during an extensive field investigation in 1998. The 1998 field investigation consisted of two components: (1) determining spatial locations of distribution system facilities (wells, tanks, pump, and hydrants) and (2) equipping hydrants with continuous-recording digital data loggers and monitoring supply sources (wells, pumps, and tanks) to measure system responses during winter demand (March) and summer demand (August) periods. Twenty-five hydrants located throughout the distribution system were equipped with data loggers to simultaneously collect information on system response (Maslia et al., 2000). The collected response data included on-off cycling of groundwater wells, high service and booster pump operations, pressure variations, storage tank water-level fluctuations, and total production.

A detailed “all-pipe” hydraulic network model was developed and calibrated to present-day conditions (1998) using the field investigation results. The reliability of the calibrated model was successfully demonstrated through a water quality simulation of the transport of a naturally occurring conservative element (barium) and a comparison of the results with data collected in March and April 1996 at 21 schools and 6 points of entry to the water distribution system. Thereafter, to describe the historical distribution system networks specific to the Dover Township area, databases were developed from diverse sources of information. These data sources included water utility pipeline installation records, quarterly billing records, NJDHSS groundwater well records, and annual water utility reports to the state board of public utilities. These data were applied to EPANET and simulations were conducted for each month of the historical period—January 1962 through December 1996 (420 simulations). After completing those 35-year/420-month analyses, source-trace analysis simulations were conducted to determine the percentage of water contributed by each well or well field operating during each month for all study subject locations.

A review of the historical network configuration revealed that the water distribution system complexity increased significantly during this period. The model inputs were appropriately adjusted to account for these historical changes. For example, the 1962 water distribution system was represented with an approximate peak production of 1.3 million gallons per day (MGD) produced from three wells that served nearly 4,300 customers (population ~17,200). By contrast, in 1996, the water distribution system had an approximate peak production of 13.9 MGD produced from 20 wells that served nearly 44,000

customers (population ~ 89,300). Appropriate adjustments were made to modeled pipe segments, storage reservoirs, and operational details. Grayman et al. (2004) present a more detailed account of the EPANET model input adjustments. Production data for the 420-month historical period is graphically represented in Figure 7-4.

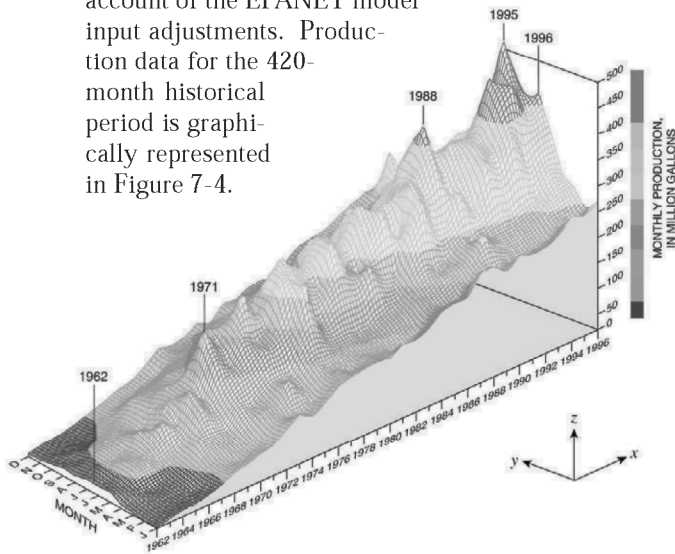


Figure 7-4. Three-Dimensional Representation of Monthly Production of Water, Dover Township Area, NJ (from Maslia et al., 2001).

To perform an extended period simulation (EPS) of the distribution of water for each of the 420 months of the historical period, information was required on network configuration, demand, and operational data. However, operational data prior to 1978 were unavailable, requiring the development of system operation parameters—designated as “master operating criteria (MOC).” The MOC is based on hydraulic engineering principles necessary to successfully operate distribution systems similar to the one serving the Dover Township area (Table 7-1). From 1978 forward, for selected years, operators of the water utility provided information on the generalized operating practices for a typical peak-demand (summer) and non-peak demand (fall) day. These guidelines were used in conjunction with the MOC to simulate a typical 24-hour daily operation of the water distribution system for each month of the historical period.

The model parameter of interest from the epidemiologic study perspective was the proportionate contribution of water from wells and well fields to locations throughout the historical pipeline networks. Thus, the distribution of water delivered to pipeline locations was the item of interest rather than the specific operations of the wells, storage tanks, and pumps (WSTP) that delivered the water. Normally, detailed WSTP operational inputs would be required for EPANET simulation. However, to simplify the simulation methodology and reduce data require-

ments, a “supply-node-link” (SNL) method of idealizing the WSTP combination was developed. In the SNL simulation method, an equivalent amount of water is supplied to the distribution system (based on estimated monthly demands and the typical daily operation of the systems). To demonstrate that the surrogate SNL simulation method supplies the distribution system with an equivalent amount of water when compared to the real-world WSTP simulation method, both simulation methods were applied to the present-day (1998) water distribution system for conditions existing in August 1998. The results obtained from these simulations produced nearly identical flows in the modeled system.

7.2.3 Simulation Techniques

Using the EPANET network model developed for the Dover Township area, hydraulic modeling was conducted whereby average network conditions were simulated for every month of the historical period

Table 7-1. Master Operating Criteria Used to Develop Operating Schedules for the Historical Water Distribution System, Dover Township Area, NJ (from Maslia et al., 2001)

Parameter	Criteria
Pressure ¹	Minimum of 15 psi; maximum of 110 psi at pipeline locations, including network end points
Water level	Minimum of 3 ft above bottom elevation of tank; maximum equal to elevation of top of tank; ending water level should equal the starting water level
Hydraulic device on-line date	June 1 of year installed to meet maximum-demand conditions
On-and-off cycling: Manual operation	Wells and high-service and booster pumps cannot be cycled on-and-off from 2200 to 0600 hours
On-and-off cycling: Automatic operation	Wells and high-service and booster pumps can be cycled on-and-off at any hour
Operating hours	Wells should be operated continuously for the total number of production hours, based on production data ²
¹ Generally, for residential demand, minimum recommended pressure is about 20 psi. However, for some locations in the Dover Township area (mostly in areas near the end of distribution lines), lower pressures were simulated. ² See Maslia et al. (2001) for production data (Appendix B) and hours of operation (Appendix D)	

(420 simulations). These simulations were completed under balanced flow conditions that utilized hydraulic engineering principles and conformed to the MOC (Table 7-1). Thereafter, using the results of the monthly network hydraulic simulations, water quality simulations (source-trace analysis) were conducted for each water source (point of entry) of the network in order to determine the monthly proportionate contribution of source water at all locations in the Dover Township area serviced by the water distribution system.

EPANET is a dynamic water quality model that has the ability to compute the percentage of water reaching any point in the distribution system over time from a specified location (source) in the network. To estimate this proportionate contribution of water, a source location is assigned a value of 100 percent. The resulting solution provided by the water quality simulator in EPANET then becomes the percentage of flow at any location in the distribution system network (for example, a demand node) contributed by the source location of interest. For the purposes of this analysis, a source-trace analysis was conducted for every month of the historical period. Source nodes were assigned a value of 100 percent in order to estimate the proportionate contribution of water to locations in the historical distribution system networks. These initial conditions were fully propagated through most of the distribution system before retrieving the proportionate contribution results (Maslia et al., 2000). Accordingly, for each monthly historical network model, 24-hour demand and operational patterns were defined and these patterns were repeated for approximately 1,200 hours to reach a state of stationary water-quality dynamics (dynamic equilibrium). For most of the analyses, hydraulic time steps of 1 hour and water-quality time steps of 5 minutes were used within EPANET. For some monthly simulations, the water-quality time steps were reduced to 1 minute to ensure that the mass balance summed to ~100 percent (range of 98 to 101 percent due to numerical approximations).

With respect to the scheduling of groundwater well operations, the EPANET model was set to utilize pattern factors corresponding to the hourly operations of supply wells. These pattern factors along with the operational extremes of storage tank water levels were manually adjusted during each of the 420 monthly network simulations to achieve balanced flow conditions. This approach to simulation was designated as the manual adjustment process. A second simulation approach designated as the genetic algorithm (GA) approach was also utilized to achieve balanced flow conditions for each of the 420 monthly networks of the historical period. This approach

required the development of an innovative methodology known as the progressive optimality genetic algorithm (POGA), which is an automated objective simulation technique (Aral et al., 2004a, b). The GA simulations utilized the balanced flow conditions obtained by the manual adjustment process as starting conditions. The GA technique was used to address the following key questions:

- If a balanced flow operating condition was achieved using the manual adjustment process, was the resulting operating condition the only way the system could have been successfully operated?
- Could alternative or additional operating conditions be defined such that system operations would also be satisfactory or even optimal?

Thus, the POGA methodology was used in conjunction with EPANET to simulate alternative and possibly optimal water distribution system operations and to assess the effects of variations in system operations on the results of the proportionate contribution simulations.

7.2.4 Simulation Results and Conclusions

Figure 7-5 shows the aerial distribution of simulated proportionate contribution results for all model nodes (pipeline junctions) for the month of July 1988, using the Parkway well field as the point of entry (source point). The simulated proportionate contribution results are divided into six intervals (1 to 10 percent, 10 to 25 percent, 25 to 50 percent, 50 to 75 percent, 75 to 90 percent, and 90 to 100 percent) and a color is assigned to all nodes within each interval (results are not shown for negligible proportionate contributions of less than 1 percent).

Simulated proportionate contribution results can also be viewed in terms of selected pipeline locations and the combination of wells or well fields that contribute water to that location. Five geographically distinct pipeline locations are selected from the historical networks to represent the spatial distribution of proportionate contribution results. These locations are identified on Figure 7-5 as locations A, B, C, D, and E. The simulated proportionate contribution of water for July 1988 corresponding to each pipeline location is shown graphically on Figure 7-6. The simulation results demonstrated that the contribution of water from wells and well fields varied by time and location. However, the results also showed that certain wells provided the predominant amount of water to locations throughout the Dover Township area. Additionally, although the pattern factors for some hours of operations showed marked differences, the simulated proportionate contributions of water using

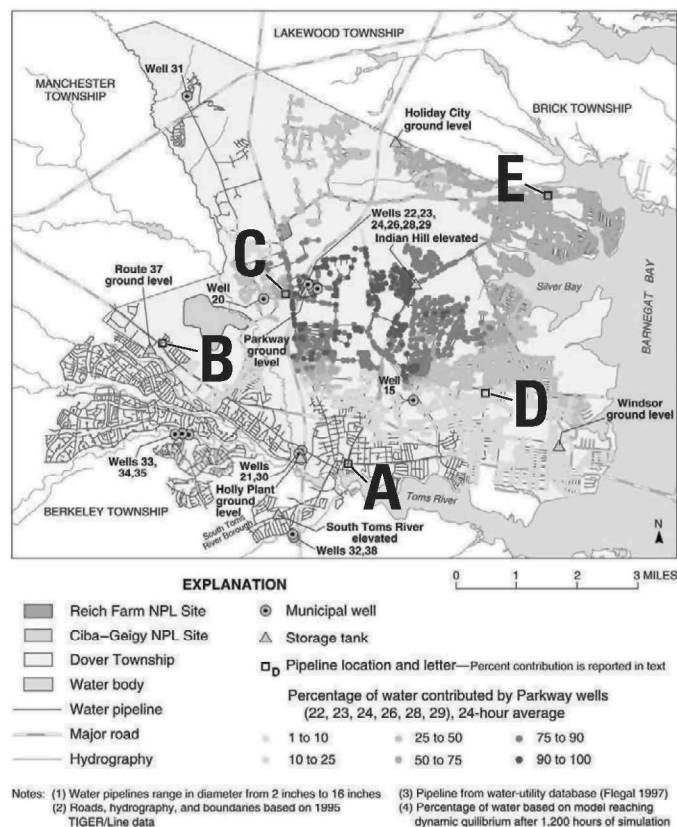


Figure 7-5. Areal Distribution of Simulated Proportionate Contribution of Water from the Parkway Wells (22, 23, 24, 26, 28, 29) to Locations in the Dover Township Area, NJ, July 1988 Conditions (from Maslia et al., 2001).

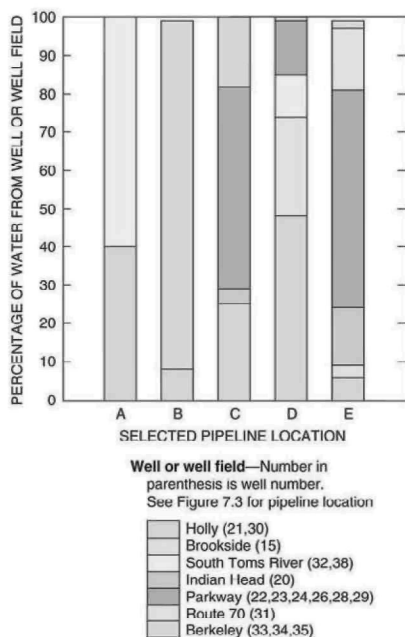


Figure 7-6. Simulated Proportionate Contribution of Water from Wells and Well Fields to Selected Locations, Dover Township Area, NJ, July 1988 Conditions (from Maslia et al., 2001).

pattern factors derived from the application of the POGA methodology showed little difference throughout the Dover Township area when compared to corresponding proportionate contribution of water simulated using the manual adjustment process. The results of sensitivity analyses conducted using the historical reconstruction process indicated the following:

- There was a narrow range within which the historical water distribution systems could have successfully operated and still satisfy hydraulic engineering principles and the MOC.
- Daily operational variations over a month did not appreciably change the proportionate contribution of water from specific sources.

Therefore, the reconstructed historical water distribution systems were determined to be the most plausible and realistic scenarios under which the 1962–1996 historical water distribution systems were operated. The health scientists conducting the case-control epidemiologic study used the resulting percentage of water derived from the different sources to derive exposure indices for each study subject.

The results from the case-control study showed that there was an association between prenatal exposure to contaminated community water and leukemia in female children (NJDHSS, 2003). For example, female leukemia cases were 5 times more likely to have occurred when exposed during the prenatal period to a high percentage of Parkway well water than were control children. The control children are those living in the study area, but were not exposed to the water from the contaminated well fields. These findings would not have been possible without the results derived from the innovative water distribution system modeling efforts. These efforts have led to developing new methods for evaluating the accuracy of modeling results and exposure classification techniques that are critical components of epidemiologic studies. Some of the innovations documented by the Dover Township historical reconstruction analysis are:

- A new approach, proportionate contribution analysis, was developed that utilized water distribution system modeling and source tracing to quantify exposure on a monthly basis for all locations historically served by the distribution system.
- Through the use of an innovative genetic algorithm approach (POGA), historical water distribution system operating schedules were

The city of Redlands lies in the San Bernardino valley of California, approximately 60 miles east of central Los Angeles. In 1981, a routine analysis for chlorination byproducts revealed the presence of trichloroethylene (TCE) in a sample of water from the Redlands water system. Subsequent water quality analyses revealed that a number of wells supplying the city were contaminated with TCE. In 1997, the perchlorate anion (ClO_4^-) was also detected in several wells. In 1996, the first of a series of lawsuits was filed in California State Court alleging that the source of these contaminants was a manufacturing facility located up-gradient from the most seriously contaminated wells.

One of these lawsuits claimed that plaintiffs were harmed by exposure to toxic chemicals that were improperly disposed of at the manufacturing site and found their way into groundwater that was subsequently extracted through the city's wells and delivered to water customers, including the plaintiffs. The plaintiffs' burden of proof requires them to establish, among other things, that they were actually exposed to contaminated water at their homes, places of work, or other locations and that the amounts of contaminants that entered their bodies as the result of these exposures were sufficient to cause harm to them.

To establish this proof, experts for the plaintiffs reconstructed the historical conditions in the water distribution system of the City of Redlands over a period from the mid 1950s to the late 1990s using the EPANET model. As part of litigation, several forensic reconstructions of water quality in the Redlands water distribution system were performed. The reconstruction involved estimates of both human exposure to toxic contaminants and whole-body intakes of these chemicals. Estimates of exposures and intakes were expressed as credibility intervals, which were calculated using Monte Carlo simulation techniques. As an example output from the analysis, Figure 7-7 illustrates the estimated upper 97.5 percent credibility limit of one plaintiff's exposure to perchlorate. Similar information was developed to describe the lower 2.5 percent credibility limit for each of the test plaintiffs in the case (Grayman et al., 2004).

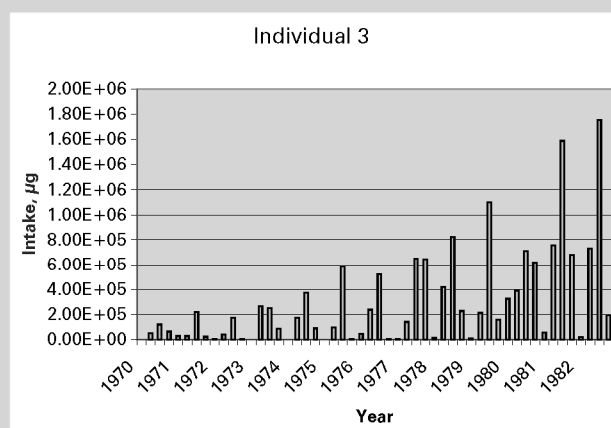


Figure 7-7. Estimated Upper 97.5 Percent Credibility Limit for Annual Perchlorate Intake by One Plaintiff (Grayman, 2004).

synthesized. Sensitivity analyses indicated that operating system changes did not appreciably change the proportionate contribution of water to Dover Township locations.

- The association between exposure and disease would not have been possible without developing the integrated approach using environmental science, engineering evaluations, and epidemiologic analyses.

Historical reconstruction of environmental exposure is not an easy task. The procedures and results summarized herein (and the detailed analyses in Maslia et al., [2001]) represent one of the most comprehensive, well-documented, and quality-controlled studies of its kind. Another example of public exposure assessment using modeling is related to the City of Redlands, California.

7.3 Application of Water Distribution System Modeling in Support of a Regulatory Requirement

The new DBPR2 regulation that is proposed for promulgation in the near future requires all water utilities that have a disinfectant residual in the distribution system to perform an IDSE unless they obtain a small-system or "40/30" waiver (EPA, 2003). Systems that can certify TTHM and HAA5 compliance data to be less than or equal to 40 µg/L for TTHM and 30 µg/L for HAA5 are not required to perform an IDSE. The goal of the IDSE is to identify compliance monitoring sites that may have high DBP levels in distribution systems. Utilities may choose to perform an SMP that involves extensive monitoring. Alternatively they may choose to perform a system-

specific study (SSS) that uses historical data, distribution system models, or other analyses combined with minimal monitoring to evaluate TTHM and HAA5 levels throughout the distribution system as the basis to select future compliance monitoring sites. This case study demonstrates how a hydraulic/water quality distribution system model can be applied to satisfy the IDSE requirements of an SSS.

Key Phrases to Characterize Case Study: Regulatory modeling, IDSE, water quality modeling.

7.3.1 IDSE Requirements Overview

The IDSE guidance manual spells out a series of suggested minimum requirements for the use of a calibrated water distribution system hydraulic model to perform an SSS. In general, the water distribution system model should be more comprehensive for the purpose of an SSS than models typically used for long-range capital improvement program analysis (e.g., master planning). A calibrated hydraulic model intended for detailed distribution system design (e.g., for system improvements) or operational studies is likely to be adequate. Because systems are always changing (e.g., population growth, industry development in network area, aging of mains), it is important that the model generally reflect system conditions and demand at the time of the IDSE SSS. A model that has not been updated or calibrated in the last 5 to 10 years is unlikely to be adequate for an SSS. The guidelines provided in the draft guidance manual are summarized below:

- EPS model that has been recently calibrated using generally accepted methods.
- An all-pipe model or skeletonized model that includes (a) at least 50 percent of total pipe length in the distribution system, (b) at least 75 percent of the pipe volume in the distribution system, (c) all 12-inch-diameter and larger pipes, (d) all 8-inch and larger pipes that connect major facilities, (e) all 6-inch and larger pipes that connect remote areas of a distribution system, and (f) all active control valves or other system features that could significantly affect the flow of water through the distribution system.
- Water demand should be allocated among the nodes of the model in a manner that reflects the actual spatial distribution of such demand throughout the system.
- A system-specific, diurnal (24-hour) demand pattern should be applied to the overall system demand.
- The model should accurately simulate seasonal system configurations and operational changes.

Once the model is established, it is then run in EPS mode until a consistent, repeating temporal pattern of water age is established at all nodes of the model. Generally, the model should be run under high DBP formation conditions (typically summer months) to estimate residence times. Based on the modeled water age results, preliminary monitoring sites are identified near locations that satisfy the sampling site requirements. Sampling sites are selected to represent:

- **High-TTHM Sites:** High TTHM values are expected at high-residence-time locations. These locations can be identified by reviewing the modeled water age at each node in the model. These sites are generally downstream of storage facilities and in remote locations. However, the regulation does not require extremes or non-representative sites to be sampled.
- **High-HAA5 Sites:** The criteria and procedure for selecting high HAA5 sites using a hydraulic model are generally the same as those described above for selecting high-TTHM sites with one important difference: the sites chosen to represent high HAA5 should have a disinfectant residual sufficient to suppress bacteria which can degrade HAAs.
- **Average-Residence-Time Sites:** Average-residence-time sites can be selected from sites with residence times close to the flow-weighted mean of all nodal residence times.
- **Near-Entry-Point Sites:** Modeled water age can be used to identify locations in the near vicinity to entry points into the water system.

Requirements for the number of monitoring sites have not yet been finalized. As a result, this case study demonstrates the general usage of models for IDSE and relies upon the 2003 draft guidance issued by EPA to illustrate the usage of models.

7.3.2 Example Application of Modeling in the IDSE Process

The following example is a hypothetical case study based in large part on an actual water distribution system. The system purchases disinfected groundwater and serves approximately 15,000 people. Water enters the distribution system from two separate interconnections to a wholesale utility. The average demand is 2.2 MGD. A north interconnection operates intermittently and provides approximately 80 percent of the demand, while the south interconnection operates at all times and provides the remaining 20 percent of the system demand. There is a 1.5-million-gallon storage tank. In order to comply with the Stage 2 requirements, the draft proposed DBPR2 states that a total of six sites are required for a utility of this size

using groundwater: one representing a site near to the predominant entry, one representing a site with average residence time, two sites representing high TTHM conditions, and two representing high HAA5 conditions.

The water utility water distribution system model has been used extensively in the past for both hydraulic and water-quality studies. It is a skeletonized model that includes all 8-inch-diameter and larger pipes and all major facilities. The pipes in the model represent 74 percent of the total length of pipe in the system and 86 percent of the total volume. The model has been previously calibrated based on two tracer studies and has been shown to have excellent agreement with observed field results. Demands have been assigned to nodes based on actual meter readings, and information from the SCADA system has been used to construct a typical diurnal water use pattern. The model is being operated in an EPS mode to simulate a 12-day period. The model has also been calibrated for use in simulating chlorine residual in the distribution system.

A series of runs of the model were performed to help understand the movement of water and water quality transformations in the system. Specific simulations included water age and chlorine residual. The results of the water-age model run are shown in Figure 7-8. This plot shows the average water age throughout the distribution system over the last 24 hours of the 2-week simulation. This period was selected to avoid the uncertainty associated with assigning initial water age in the system. The plot illustrates the nodes in the vicinity of the predominant northern interconnection that receive water with an average age of less than 2 hours. As also shown, the average water age increases significantly for areas that are further from the interconnections. The demand flow-weighted average water age for delivered water was calculated to be 27 hours. However, water age can also vary quite significantly over the course of a day in water systems, largely due to the impacts of storage tanks. This is illustrated in Figure 7-9, which depicts the minimum water age at each node over the same 24-hour period. This is also shown in the plot in Figure 7-10 for Node J-456 in the vicinity of the tank. The IDSE guidance does not require utilities to explicitly consider the effects of tanks on diurnal variations in water age, and thus on the formation of DBPs. If Node J-456 was selected as representative of high DBP because of its high water age, it would be expected that the DBPs would only be high during the part of the day when water is being discharged from the tank.

The model was also used to determine the chlorine residual throughout the system. Figure 7-11 contains a plot of the minimum chlorine residual throughout the system. It is important to note areas with high

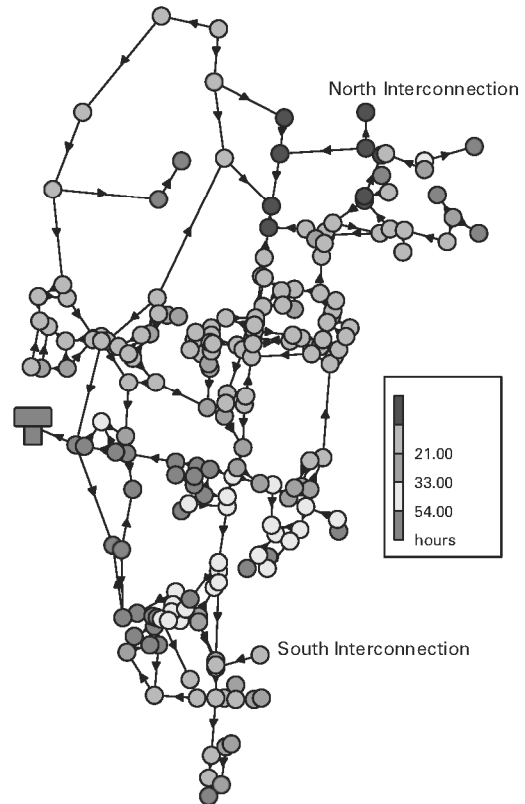


Figure 7-8. Average Water Age in the Distribution System Over Last 24 Hours of a 2-Week Simulation.

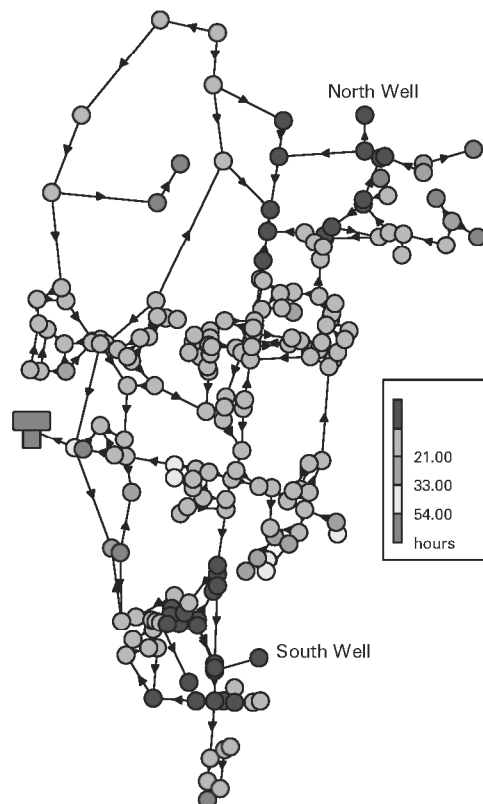


Figure 7-9. Minimum Water Age in the Distribution System Over Last 24 Hours of a 2-Week Simulation.

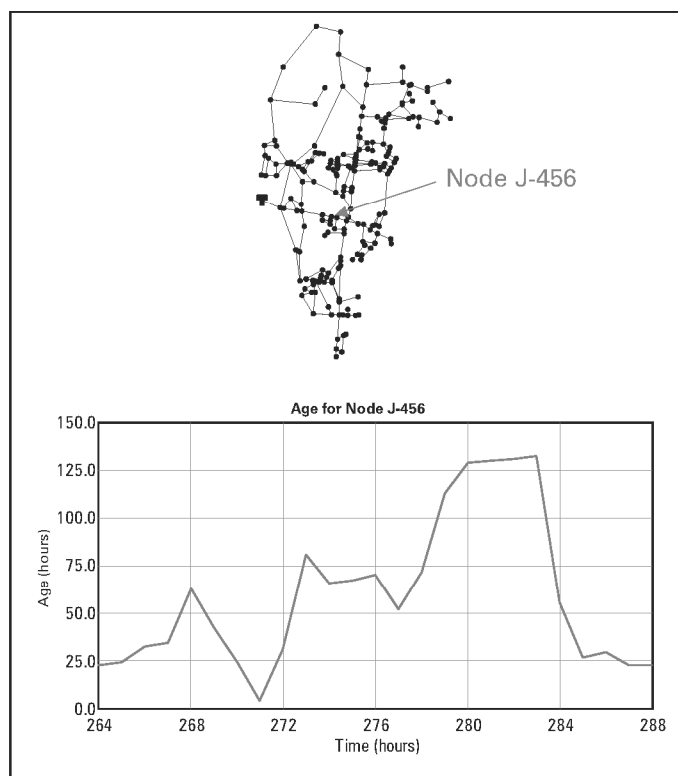


Figure 7-10. Diurnal Water Age at Node J-456.

residence time and low residual for high-TTHM sites and high residence time and high residual for high-HAA5 sites. This information can be used to avoid selecting monitoring sites that are to be used as representative of high HAA5 concentrations. The current ability to accurately model HAA5 in a distribution system is limited. However, research has shown that depressed chlorine residual can result in biodegradation of HAA5, thus lowering the HAA5 concentrations even for older water. Figure 7-11 also shows a small area in the southwestern portion of the system that the model predicts to potentially experience chlorine residuals less than 0.2 mg/L of chlorine.

Based on the modeling results, various zones were defined in the distribution system representing areas that are appropriate for different types of compliance monitoring requirements (Figure 7-12). In actual use, information generated by the model would be supplemented by historical field data. The zones shown in the plot include:

1. Nodes in the vicinity of the predominant north connection with water age less than 2 hours representative of near entry locations;
2. Nodes with average water age in the range of 21 to 33 hours that represent locations that approximate the average residence time of 27 hours;

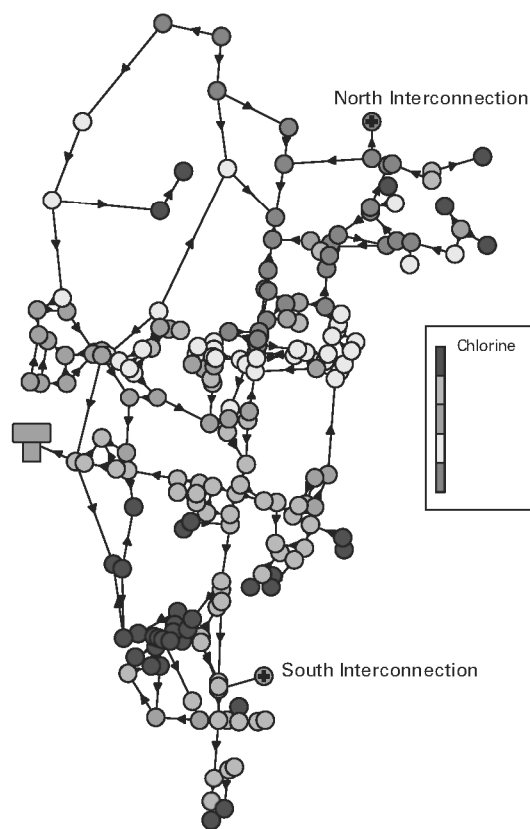


Figure 7-11. Minimum Chlorine Residual in Distribution System Over Last 24 Hours of a 2-Week Simulation.

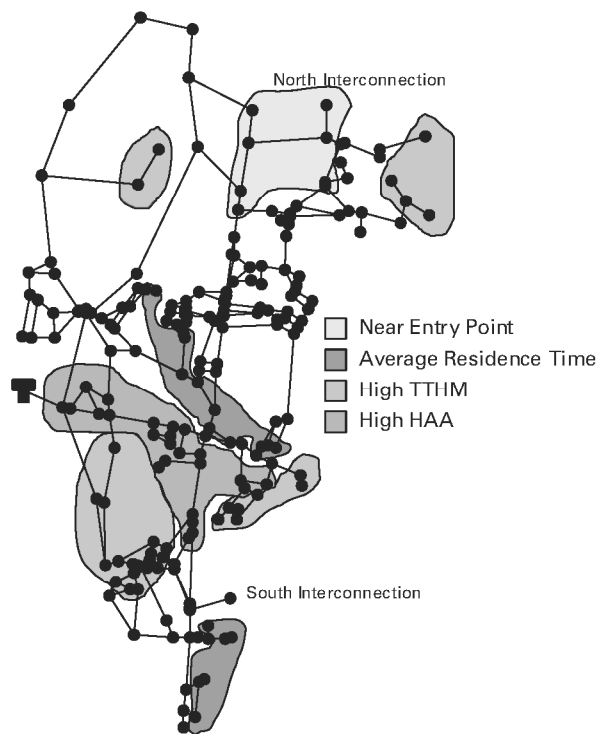


Figure 7-12. Zones Representing Potential Monitoring Locations for IDSE Based on Modeling.

3. Nodes with residence times that exceed twice the average water age (> 54 hours) and have a minimum chlorine residual exceeding 0.20 mg/L representing potential high-HAA5 sites; and
4. Other nodes with residence times that exceed twice the average water age (> 54 hours) representing potential high-TTHM sites.

As illustrated by the case example, if a detailed, calibrated EPS model is available, the model represents an efficient means of defining the compliance monitor locations as required under the forthcoming regulation.

7.4 Use of Water Distribution System Models in the Placement of Monitors to Detect Intentional Contamination

The increasing concern over the potential for intentional contamination of a water distribution system has led to interest in the placement of monitors to detect contamination and to serve as part of a rapid detection system. Design of such monitoring systems must include decisions on the type, number and location for the monitors. Water distribution system models can play a significant role in the decision making by providing a quantitative mechanism for determining the movement of a contaminant through the distribution system and testing the effectiveness of a monitoring system design.

To illustrate this application, a red team-blue team concept is used (Grayman et al., 2005). The red team-blue team concept is part of “war gaming” that is widely used today as a mechanism for training and development and testing of security plans. The red team acts as the aggressor and the blue team acts as the defenders. Each team has different types and amounts of information available to them and different rules or constraints that they must follow. In this case study, network models are used in two modes to assist in evaluating monitoring networks:

1. As part of a red team-blue team exercise to demonstrate the effectiveness of manual selection of location of monitors as part of a CWS.
2. As part of an optimization model to select the best locations for monitors based on a stated metric for measuring the effectiveness of the monitoring system.

Key Phrases to Characterize Case Study: Water security, contamination, optimization, monitor placement

7.4.1 Red Team-Blue Team Exercise

In this simulated exercise, the red team attacks a water distribution system by adding a harmful chemical to the water. The red team is provided with limited information on the distribution system, a number of potential locations where they can inject a contaminant, and predetermined information on the characteristics of the contaminant (quantity and lethality of the contaminant). The blue team represents the water utility and attempts to protect the water system by installing three monitors as part of a CWS that detects contaminants. It is assumed that they have extensive information on the design and operation of the distribution system but no firm information on where the attackers may choose to introduce the contaminant or the nature of the contamination scenario.

The water distribution system network used in this exercise is a skeletonized version of a major pressure zone of a water distribution system in California approximating the conditions (design and operation) in the mid 1990s. The system is fed by two sources; one that operates continuously and one that operates only during the day. There are three storage facilities located in the network. This network is one of the example networks provided as part of the EPANET model. The simulation performed in the exercise is a 24-hour EPS starting at 7AM. The model representation of the network is shown in Figure 7-13. This figure also illustrates the relative nodal demands, and the typical flow directions and magnitude during the day. This plot is given only to the blue team to provide them with information on the design and operation of the system. The red team is provided

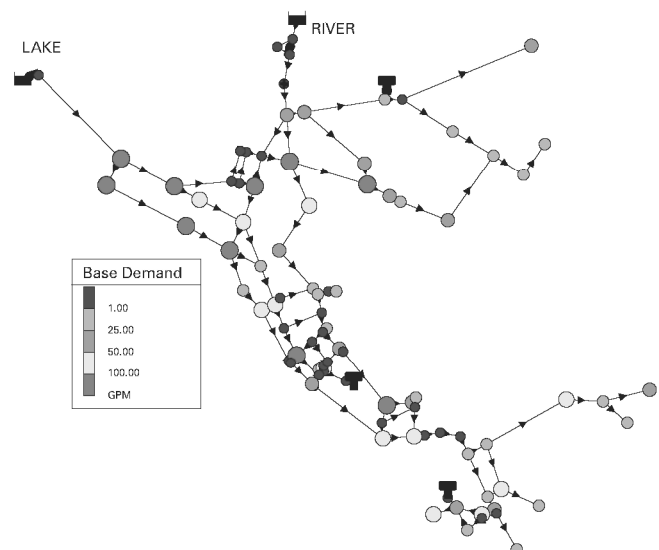


Figure 7-13. Water Distribution System Characteristics.

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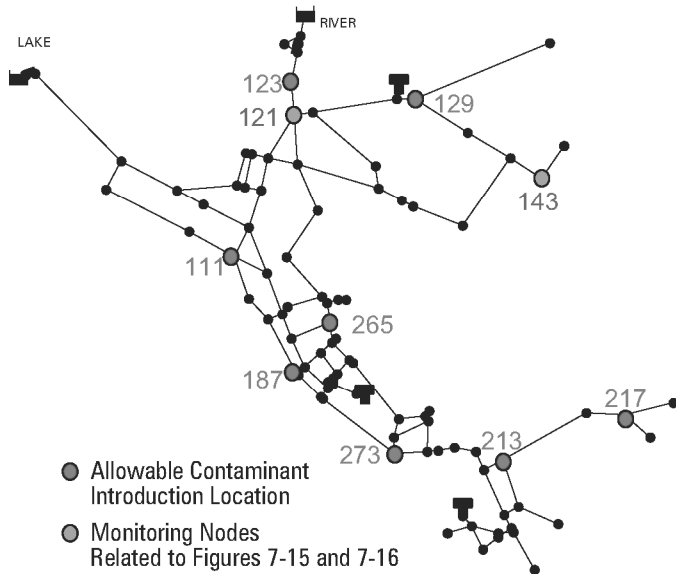


Figure 7-14. Allowable Contaminant Introduction Locations.

only with a map of the distribution system showing eight potential sites that can be used to introduce a contaminant (Figure 7-14).

Following the selection of points of attack by the red team and selection of monitor locations by the blue team, the contaminant introduction is simulated using the EPANET model. The movement and concentration of the contaminants are then viewed graphically by animating the movement of the contaminant in the distribution system in the EPANET model. The time history of contaminant concentrations is also viewed at selected nodes in the distribution system. The effectiveness of monitors is illustrated by graphing the concentrations of the contaminants at monitoring nodes and assessing whether (and how quickly) the monitors will serve their purpose of detecting the contaminant. Figures 7-15 and 7-16 show the concentrations resulting from 8 hours of contamination at node 123 starting at 11 a.m.

In Figure 7-15, the resulting contamination at a

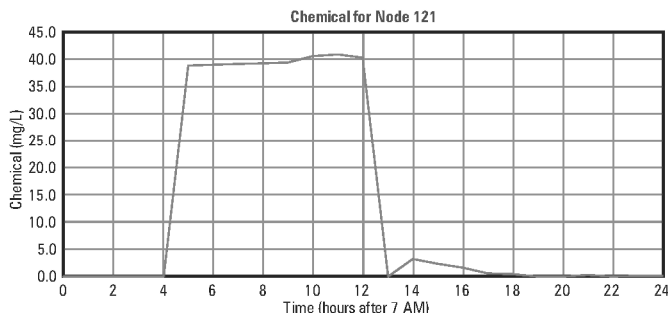


Figure 7-15. Contaminant Concentration Just Downstream of Contaminant Introduction Location (Node 121).

node located 1500 feet immediately south of the injection point is shown. As expected, the contaminant moved very rapidly and reached this node in less than an hour after the injection. If a monitor was located at this node, and rapid analysis and response occurred, it could be very effective as an early warning for most of the distribution system. Figure 7-16 illustrates concentrations resulting from the same contaminant introduction location. This node is located near the eastern edge of the distribution system approximately 2.5 miles downstream of the contaminant introduction location. As illustrated, the concentration of the contaminant remained about the same but the travel time to this point was approximately 7 hours. For this injection scenario, a monitor located at this point would be relatively ineffective as a warning device for most of the distribution system because of the significant time lag.

In the exercise, most red team members tend to select contamination introduction locations that they perceive would result in the most widespread impacts. The most often selected sites were those near to the water sources. Little attention is generally given to the amount of dilution that would result at a particular location. Blue team members tend to select monitoring locations that cover a wide range of locations. Frequently, the three allowable monitors will be located in the north, central, and southern portions of the distribution system.

7.4.2 Application of Optimization Model

The optimization model used in this demonstration is a methodology developed by Ostfeld and Salomons (2004). The model links EPANET and a genetic algorithm in an overall framework for optimally allocating monitoring stations, aimed at detecting deliberate external contamination into water distribution system nodes. The model operates under extended period (unsteady) hydraulics and water quality conditions. The optimization routine determines the monitor placement to detect contaminants in order to minimize the exposure of

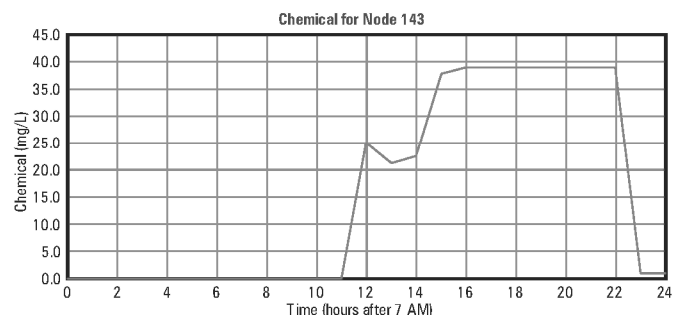


Figure 7-16. Contaminant Concentration Far Downstream of Contaminant Introduction Location (Node 143).

customers above an allowable minimum concentration. The algorithm can be used to study contamination of fixed duration, quantity, or location or can simulate contamination under stochastic conditions. There are several model parameters that can be specified to control the number of monitors, the allowable contaminant introduction locations, the characteristics of the event, and whether the event characteristics and demands are to be considered as stochastic variables.

In one application of the model, it was assumed that the pollutant could be introduced at any single node of the distribution system at any time, all with the same injection probability. The following additional assumptions were made:

- The maximum contamination exposure volume to the public above which an alarm signal of the monitoring stations is required is 25 gallons.
- The water is considered contaminated above 1 mg/L.
- The pollutant flow discharge is 2 kg/min for 5 minutes (i.e., a total of 10 kg of a solution of 100 percent is introduced within a total of 5 minutes).
- The pollutant flow discharge of the contaminant introduced and the consumer demands are deterministic.
- The monitoring stations are providing real-time data and detection alarms.
- All monitoring stations have a detection sensitivity of 1 mg/L.
- 3 monitors are to be placed.

The model suggests placing monitors at nodes 143, 181, and 213 with a detection likelihood of 0.4354 (i.e., there is a probability of about 44 percent that the contaminant will be detected prior to the consumption of more than 25 gallons at a concentration higher than 1 mg/L). The location of the monitors is shown in Figure 7-17. As illustrated, the selected monitor locations were relatively evenly spaced around the network.

Other evaluated scenarios looked at a different number of allowable monitors, the allowable contaminant introduction locations, the critical exposure threshold, and representation of contaminant quantity and nodal demands as stochastic variables. Though the exact “optimal” locations varied slightly between the different runs, typically the monitors were placed throughout the network. However, the effectiveness of the monitoring network, as measured by the detection likelihood does vary considerably between scenarios.

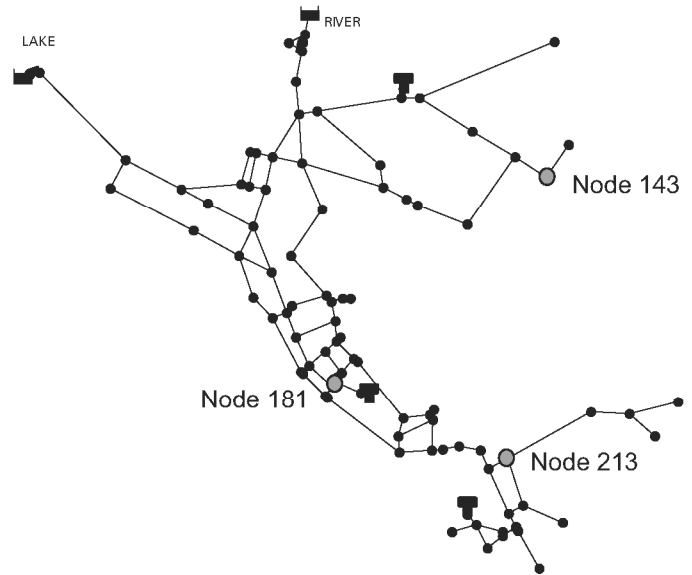


Figure 7-17. Monitoring Locations Selected by the Optimization Model.

7.4.3 Case Summary

The red team – blue team exercise serves as a good mechanism for demonstrating both the dynamics of contaminant movement in the distribution system and the potential effectiveness of monitors. Application of the optimization model, both as a demonstration procedure and as a practical tool, provides a method that moves the monitor placement from a purely intuitive process to a quantitative procedure. Both the exercise and the optimization tool show the importance in minimizing delays in the detection, notification, and response process. Even an added delay of an hour or two can lead to a significant increase in the number of customers that would be impacted by a contamination event.

7.5 Case Study – Use of PipelineNet Model

This case study focuses on the application of the PipelineNet model, which incorporates both GIS and the EPANET model discussed in the previous chapters of this reference guide. The supporting investigations were primarily sponsored by the Awwa Research Foundation (AwwaRF) and EPA with work performed by a consulting firm (SAIC) and assistance from water utility personnel (Ron Hunsinger, Bill Kirkpatrick, Dave Rehnstrom) working at the East Bay Municipal Utility District (EBMUD), Oakland, CA. The text and figures are adapted from AwwaRF report 2922 prepared by Bahadur et al. (2003).

Key Phrases to Characterize Case Study: hydraulic and water quality modeling, placement of monitors, exposure modeling, contamination assessment, contamination response tools, geospatial analysis.

7.5.1 Overview

PipelineNet is an EPANET/ArcView¹-based model, and uses the same hydraulic engine as EPANET. The EPANET portion of the model can simulate the fate and transport of potentially introduced contaminants in a water distribution system. The ArcView (or the GIS layer) portion of the model can relate the geospatial components of the simulated impact. The GIS layer allows for geo-features and map display with an overlay of model output. This feature is particularly useful in applications such as emergency response, determining optimal placement of sampling, and monitoring instruments.

AwwaRF and EPA jointly funded a project to develop techniques to locate monitoring points in a distribution system, determine appropriate timing and frequency of monitoring, and establish monitoring techniques and relevant water quality parameters. For this purpose, a fully calibrated extended period simulation (EPS) network model hypothetically representing a portion of EBMUD was developed using PipelineNet. This study area network model represents 16 of the 123 pressure zones in the overall EBMUD distribution system. The study area contained 27 tanks, 748 miles of pipes, 62 pumps and 17,997 pipe segments with diameters equal to or greater than 2 inches. Figure 7-18 shows a partial view of the hypothetical network of pipelines.

7.5.2 Model Calibration

The network model was calibrated by comparing the observed (SCADA data) and simulated (PipelineNet model) water level in 25 tanks located in the study area. The primary focus of the calibra-

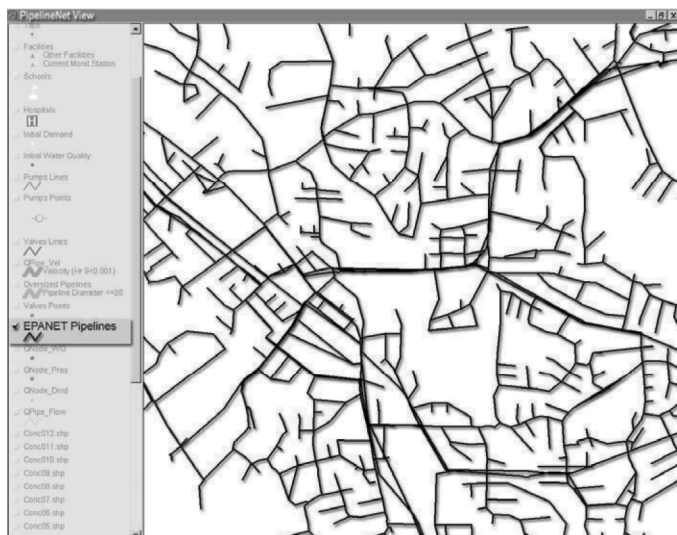


Figure 7-18. Hypothetical Water Distribution System Showing Pipelines.

tion was to match the shape of the observed water level in the tanks. The model calibration was performed for a 24-hour time interval using data measured on July 1, 2001. To further enhance calibration, the pump characteristic curves were used to achieve a good comparison between simulated and observed tank levels. The flow value of the characteristic curve was changed as necessary to reflect field conditions. Each pump was operated with time controls.

7.5.3 Monitoring Site Location Methodology

A hierarchical selection process was developed to locate monitoring stations in the distribution system. A three-step approach was employed based on model inputs, outputs, and GIS layers (see Figure 7-19).

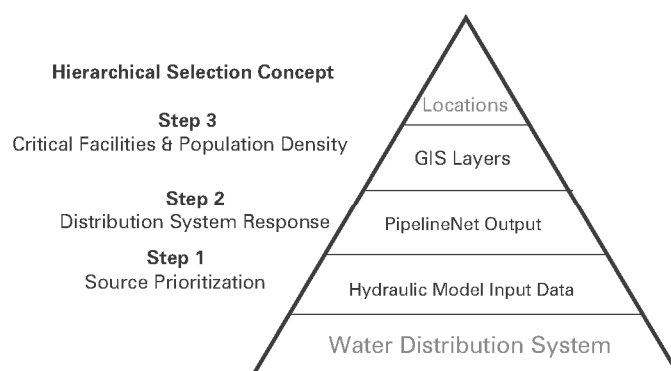


Figure 7-19. Conceptual Diagram Showing the Ranking and Prioritization Methodology.

In the first step (source prioritization factor), all the elements of the water distribution system are assumed to be available for monitoring. This universe is then reduced to a smaller set based on accessibility (location) and amenability (e.g., eliminating dead ends, crosses, tees, junctions with different pipe material) to monitoring. Initially, all nodes are considered available for monitoring and are assigned a score of 1. Subsequently, all the nodes, which are either not amenable or not accessible, are assigned a score of 0. This reduced the number of pipes available for monitoring from 17,997 to 14,938. Therefore, only the 14,938 nodes with a score equal to 1 are considered for Step 2 (described below).

In the second step (distribution system response factor), the PipelineNet model is run to quantify the distribution system response in terms of flow, velocity, and pressure. Concentration of water quality parameters could also be considered in this ranking procedure but was not included as a factor in this case study. Each system response parameter has equal

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weighting and is assigned an initial score of 1 for every pipe. Thereafter, based on the run, the scores are re-assigned values ranging between 1 and 10, where a score of 10 would indicate a higher level of concern. For any given parameter, the user can determine the distribution of scores over the parameter range. For example, a score range of 10 to 1 could be distributed over a flow range of 0.001 to 100 gpm. The PipelineNet model and Bahadur et al. (2003) provide some guidance for assigning scores, but the user can select any score based on the requirements of the analysis.

In the third step (critical facilities and population density factor), user defined buffer zones (polygons) are created around critical facility locations. In addition, areas of low-, medium-, and high-population density are delineated by the creation of polygons. Pipes closest to the critical facilities and/or near high population density areas are assigned a score of 10.

The total score for each pipe based on Steps 2 and 3 are computed. These final scores are linked to the GIS pipeline layer. The user can identify areas where monitoring stations should be placed based on the display of pipes with high scores. Figure 7-20 shows the pipes in the hypothetical network with scores greater than 27 overlaid with critical facility locations. The methodology outlined above for selecting the location of monitoring stations is a subjective procedure that requires input and judgment from water utility personnel. It would not result in a common solution for all distribution systems but can incorporate the specific needs and objectives of the participating water utility.

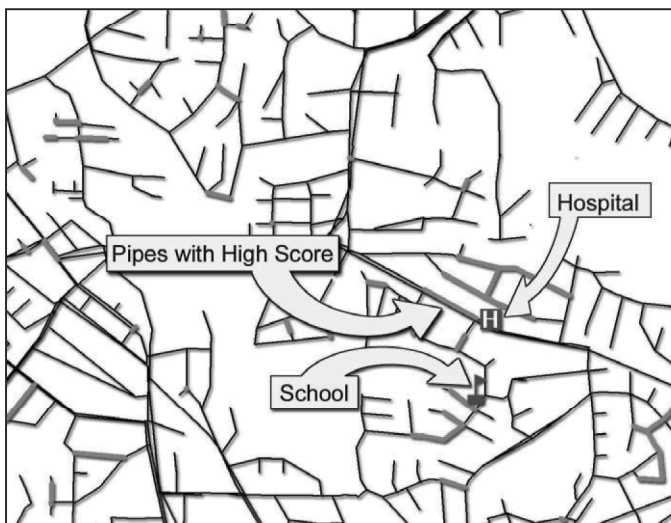


Figure 7-20. Hypothetical System Showing High Score Areas (>27) Overlain with Hospitals and Schools.

7.5.4 Response and Mitigation Tools

In addition to the monitoring site location methodology, three additional tools were developed as part of this case study to enhance the capability of PipelineNet in the areas of emergency response, mitigation, and normal operations. These three tools are briefly described in the following subsections.

7.5.4.1 Consequence Assessment Tool

The consequence assessment tool of PipelineNet provides the ability to quickly identify and quantify the population, infrastructure, and resources at risk from a contaminant event. For a defined contaminated area, this tool can calculate:

- total population at risk,
- number of taps contaminated,
- miles of pipe contaminated,
- total number of hospitals and beds for each hospital, and
- total number of schools and student population.

7.5.4.2 Isolation Tool

The isolation tool of PipelineNet provides the ability to change the status (open or closed) of any pipe in the distribution system. After completing a water quality simulation and examining the contaminant distribution from the event, this tool could be used to close off one or more pipes to control the flow of water. The model would then be re-run, reflecting these new hydraulic conditions, and the output examined to determine if this mitigation step was successful in limiting the area of contamination.

7.5.4.3 Spatial Database Display Tool

PipelineNet's spatial database display tool can overlay the EPANET model output with various geospatial properties. The spatial database display tool of PipelineNet has nineteen criteria to choose from. The users can select any combination(s) of the available criteria. For illustration purposes, Figure 7-21 shows the display of three criteria: oversized pipes (diameter >30 inches), current monitoring locations, and low velocity (velocity < 0.001 FPS) pipes.

7.5.5 Case Summary

The case study demonstrates that the PipelineNet model can be used to perform a variety of practical analyses to locate monitoring systems. Three additional tools are available that enhance PipelineNet's capability in the areas of emergency response, mitigation, and normal operations. However, to effectively utilize the PipelineNet model, the utility must have a calibrated EPS EPANET-based network model and utility-specific GIS data. At the

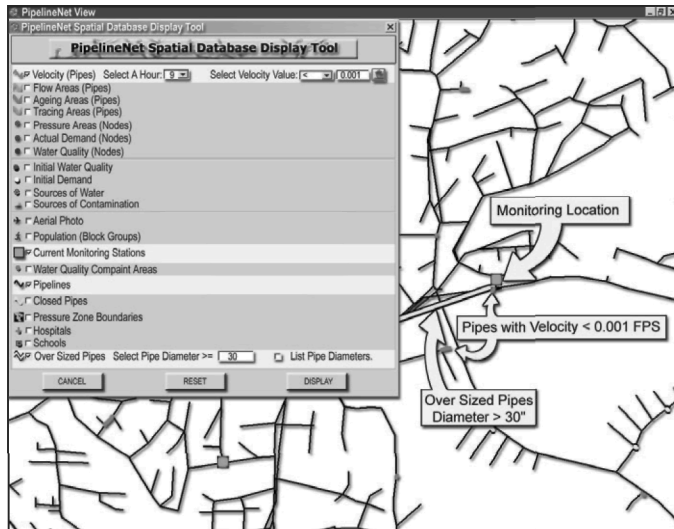


Figure 7-21. Display of Low-Velocity Pipes, Oversized Pipes, and Current Monitoring Stations Using the Spatial Database Display Tool.

time this reference guide was being written, the model is slated to undergo additional enhancements to improve the following: contaminant database, consequence assessment, inclusion of time of travel, conversion from ArcView 3.2 to ArcGIS, and establishment of links to SCADA data.

7.6 Use of Threat Ensemble Vulnerability Assessment (TEVA) Program for Drinking Water Distribution System Security

In response to the increased focus on the vulnerability of drinking water systems to the intentional introduction of chemical, biological, or radiological contaminants, EPA is developing the Threat Ensemble Vulnerability Assessment (TEVA) Program. TEVA, when completed, will be capable of analyzing the vulnerabilities of drinking water distribution systems, measure public health and economic impacts, and design and evaluate threat mitigation and response strategies. TEVA is a probabilistic framework for assessing the vulnerability of a water utility to a variety of contamination attacks. Monte Carlo simulations generate ensembles of scenarios, and statistics are analyzed to explore the feasibility of scenarios, identify vulnerable areas of the water distribution network, and analyze the sensitivity of the model to various parameters.

The TEVA team includes several individuals from various organizations. The key EPA TEVA leads are: Regan Murray, Robert Janke, and Jim Uber.

Key Phrases to Characterize Case Study: hydraulic and water quality modeling, placement of monitors, vulnerability assessment, exposure modeling, contamination assessment, contamination response tools, probabilistic analysis, economic impact assessment, threat mitigation strategies.

7.6.1 TEVA Overview

TEVA incorporates a probabilistic framework for analyzing the vulnerability of drinking water distribution systems. Figure 7-22 outlines the major components of the framework: the stochastic modeling of scenarios, the analysis of potential impacts, and the assessment of threat mitigation strategies. Together, these three components present an integrated view of the vulnerability of a unique distribution system to a wide variety of contamination threats and the potential for a water utility to decrease this vulnerability through a set of mitigation strategies. Preliminary design and implementation has been completed for a core set of components. A longer-term research effort is being planned for the other components.

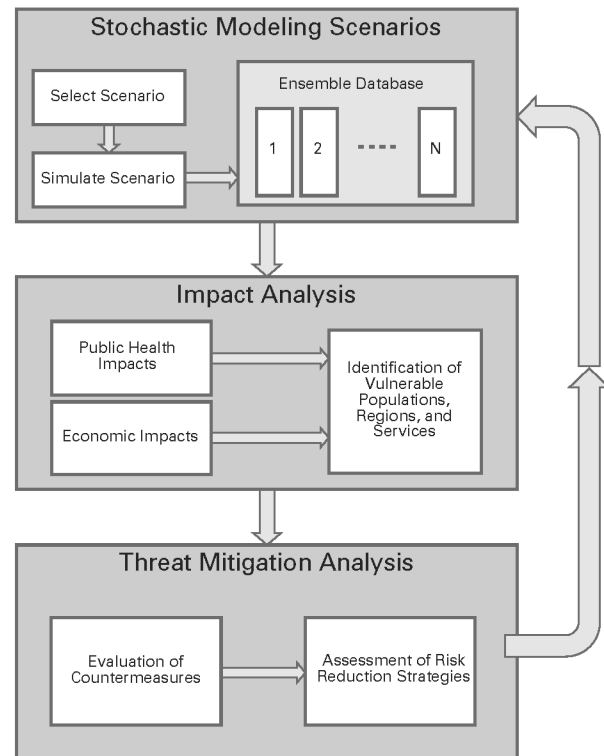


Figure 7-22. Threat Ensemble Vulnerability Assessment Framework.

Without specific intelligence information, one cannot predict exactly how a terrorist group might sabotage a water system. Therefore, TEVA is based on a probabilistic analysis of a large number of likely threat scenarios. While the number of possible variations on

scenarios is nearly infinite, the vulnerability of the system can be assessed by selecting a “large enough” set of likely scenarios. TEVA creates a threat ensemble, or a set of contamination scenarios, based on varying the type of contaminant, the amount and concentration of the contaminant, the location of the contaminant introduction into the distribution system, and the duration of the contamination event. The vulnerability of the system is based on an assessment of the entire threat ensemble. The following subsections present an overview of the aforementioned three key modeling elements.

7.6.1.1 Stochastic Modeling

The stochastic modeling element involves three steps: selection of the threat ensemble, simulation of the ensemble, and storage of the output in the ensemble database. The threat ensemble is a collection of scenarios that will be simulated. One scenario may represent, for example, the injection of a 55-gallon drum containing a biotoxin mixture into one node of a particular distribution system with 1,000 nodes. This scenario can be repeated for each of the 1,000 nodes, generating a threat ensemble of 1,000 scenarios. One could vary other parameters, such as contaminant type, quantity, concentration, location, or duration, to generate other threat ensembles. Current work is determining how to best select a large enough threat ensemble in order to accurately assess vulnerability. While a larger number of scenarios will allow for the consideration of more threats, constraints on computation time require that the number of scenarios be minimized.

Next, each scenario in the threat ensemble is simulated using a network hydraulic and water quality model. In TEVA, an EPANET based network model is generated with all necessary data for running the simulations. The EPANET model currently includes first order decay of constituents. Soon to be completed upgrades to EPANET will allow modeling of the fate and transport of multiple dissolved constituents in distribution systems (Uber et al., 2004a). These upgrades will permit the modeling of reactions at the pipe wall and in the bulk flow and enable the inclusion of chemical reaction products, thereby resulting in more accurate estimates of human exposure and health risk. The results of the stochastic modeling of the threat ensemble are stored in the ensemble database, allowing for later analysis of the data in the other components of TEVA.

7.6.1.2 Impact Analysis

The Impact Analysis element uses the data stored in the ensemble database to estimate likely public health impacts and economic impacts. Public health impacts include injuries, disease, illness, and deaths. People can be exposed to contaminants from ingestion of

water, inhalation of volatilized chemicals or particles, and/or contact with the skin. Depending on the contaminant, specific dose-response models can be employed to estimate the various health endpoints. For many threat agents, reliable data for such models are lacking, and the ensuing uncertainty in the results must be understood. For contagious diseases, dynamic models of disease transmission also must be included in order to accurately assess health impacts.

Economic impacts include restoration costs (cleanup, treatment, remediation, and decontamination), denial of service costs (providing alternative sources of water), and other costs, such as medical costs (hospitalization, vaccines). Psychological costs related to consumers’ loss of trust in the water supply system are very difficult to estimate. The distribution of impacts will be calculated from the ensemble database, thereby providing an estimate of the expected impacts for the ensemble of threat scenarios.

7.6.1.3 Threat Mitigation Analysis

The Threat Mitigation element explores various mitigation strategies such as the use of early warning systems (sensors and data analysis tools), operational approaches (chlorine boosters, back-up equipment), and emergency response methods (isolation of part of the system, public notification). A range of mitigation strategies can be evaluated with the TEVA simulations using health risk and economic impact analyses to rank and select the best alternative for a set of scenarios (Uber et al., 2004b). This will enable a quantitative analysis of the benefits of implementing various strategies.

7.6.2 Application of TEVA to a Water Distribution System for Optimal Monitoring

The TEVA computational framework (Murray et al., 2004, Uber et al., 2004b, Murray et al., 2005) has been applied to three sizes of distribution systems, each differing in population by approximately one order of magnitude. The results shown for this case study illustrate that TEVA has the potential to help water utilities assess the contaminants to which they are most vulnerable, identify the most vulnerable regions of their distribution systems, and select the most appropriate mitigation strategies for their system.

Many different forms of contamination monitoring systems have been proposed, using water quality sensors, composite or grab sampling, and various numbers and locations of sensors. Any contamination monitoring and surveillance program will be budget constrained. Optimizing the placement of a fixed number of monitoring stations plays an important role in the design of the monitoring system. Selecting the best locations for conducting a routine sampling

program to serve as a monitoring and surveillance program for detection of intentional contamination can be considered an integer linear programming problem in which a quantity is optimized subject to a set of constraints (Berry 2005). Formal optimization methods and heuristic methods have been applied to solve such problems. In this case study, a Greedy heuristic algorithm is used to locate monitoring stations, given a defined budget or number of monitoring stations, in order to minimize health impacts. The following is an example of using TEVA to evaluate and optimize (in a limited fashion) the design of a contamination monitoring system for a water distribution system.

7.6.2.1 Simulation Overview

For the purposes of this analysis, an “all-pipes” EPANET network model for the sample distribution system was generated. There are 1,062 miles of pipe represented in this network model. This system contains approximately 12,000 nodes, has an average daily demand of approximately 20 million gallons, and an estimated population of 130,000. Approximately 6,000 potential sampling locations were selected randomly from the nearly 12,000 nodes by considering that each node had a 50 percent probability of inclusion. This pruning was used to make the problem less computationally intensive and emphasize that an optimal placement of monitoring stations will likely be difficult given legal, financial, or logistical constraints for placing and managing monitoring stations.

To simulate a contamination scenario, many parameters must be specified, including characteristics of the contaminant, the contaminant-introduction scenario, and the consumption patterns of the population. In order to represent the range of possible parameter values, the TEVA computational framework uses simulation to vary parameters, such as contaminant type, quantity, concentration, location, rate, or duration, to generate threat ensembles (collections of many threat scenarios) which collectively can be analyzed for health impact statistics. All nodes (a grouping of service connections) in the distribution system are considered equally likely introduction points. Biological and chemical contaminants can be considered, and contaminant introduction can last from a few minutes to hours to days. For the purposes of this analysis, a biological agent was considered as the contaminant and the introduction duration was 24 hours, at a rate of 8.675 liters per hour, and a mass rate of 1.45×10^{11} organisms per minute.

The health impacts are affected by factors such as dose-response relationships, lethal doses, time-to-onset of symptoms, time for effective medical intervention, and the time delay for transporting and

analyzing samples in laboratories. Health impacts to a population will increase with an increase in the time required to implement an effective response for a known contamination event. Considering these factors, modeling and simulation analyses, such as those presented here, must be performed on a contaminant specific basis. The health impact statistics can include mean infections/illnesses or mean fatalities. Infection/illness is a function of the dose of organisms or contaminant ingested and the probability of illness caused by that dose, as determined from the contaminant dose-response curve (in this case, *Salmonella*). Mean infections/illnesses are statistically determined from the probabilistic analysis of all threat scenarios. Maximum infections resulted from introduction at the node delivering the maximum health impacts.

Although there was one worst case node, there were approximately 60 threat scenarios (contaminant introduction locations), which delivered at least 50 percent of the maximum lethality. The maximum number of lethality was approximately 13,000.

In this TEVA-simulated analysis, the benefits of two composite grab sampling programs were evaluated (daily and every 48 hours) and compared to the benefits provided by a system of real-time (inline, contaminant specific) sensors. The benefits of the sampling or monitoring programs are measured by the hypothetical reduction in public health impacts. In this analysis, sample location designs are based on minimizing the mean number of fatalities for 2 sampling frequencies: 24 hours and 48 hours. Six sampling/sensor station placement scenarios were evaluated in this analysis: 5, 10, 15, 20, 30, and 40 locations for each program. The Greedy algorithm used in this analysis will provide an optimal solution for minimizing public health impacts.

For the purposes of this analysis, the grab samples are considered to be filtered samples. Filtered samples represent composited samples that have been collected and concentrated through a filtration device to better enable the collection and analysis of biological organisms. Also, real-time water quality monitors are assumed to detect chemical contaminants or biological organisms through the change in water quality, such as determined by the reduction of chlorine residual or increase in turbidity. These real-time and sampling-based analyses are considered ideal, meaning that detection limits were zero and the biological contaminant was always detected.

7.6.2.2 TEVA Analysis Approach

This analysis considers attacks at every non-zero demand node, totaling approximately 10,000. Only non-zero demand nodes are considered because they represent service connections that are using water from the distribution system on a regular basis and,

therefore, could possibly be used for contaminant introduction. Statistically analyzing the approximately 10,000 threat scenarios provides an estimate of the hypothetical health impacts in terms of average health impacts (e.g., fatalities or illnesses) and maximum impacts. Average impacts could be expected to result if a saboteur had no knowledge of where best to attack and simply randomly chose a node location for contaminant introduction. Maximum health impacts correspond to a relatively small set of contaminant introduction node locations (threat scenarios) that maximize health impacts to the associated receptors.

The contaminants were modeled as tracers, i.e., free of hydrolysis, chlorination, pipe wall, or biofilm reactions, which would largely decrease the contaminant's effectiveness in causing harm to public health (an extended version of EPANET is undergoing testing to allow multi-species modeling of contaminants). Contaminants are modeled using a mass injection rate, zero volume added, which consequently does not influence the hydraulic properties of the network, i.e., flow increase, decrease, or reversal of flow.

Hydraulic and water quality simulations were run for 192 hours. The disease-causing agent or contaminant was considered to be a hypothetical, biological contaminant that is expected to cause infection (50 percent of the time) in an adult when 10,000 or more of the organisms are ingested. The incubation period was assumed to be 24 hours, and the time for effective treatment was 48 hours after the onset of symptoms. After 72 hours, people either recovered or died. A sigmoidal dose-response curve was assumed for the ingestion of organisms with the untreated fatality rate at 16 percent of those infected.

7.6.2.3 TEVA Analysis Results

Figure 7-23 compares the reduction in mean infections provided by a routine 24-hour filtered sampling program, a routine 48-hour filtered sampling program, and a real-time, continuous, monitoring program. Similarly, Figure 7-24 compares the reduction in the maximum number of infections of the same 3 monitoring programs. Again, this scenario assumes contamination by an individual who understands distribution systems and has the knowledge and resources to determine the maximum impact location(s).

It is assumed that the computer simulations and the monitoring/surveillance programs are successful in reducing public health impacts by preventing further consumption after detection. The results show that there is not a significant difference between daily (24-hour) sampling and 48-hour sampling in terms of reducing health impacts. As expected, the continuous monitoring program detects the incident much earlier

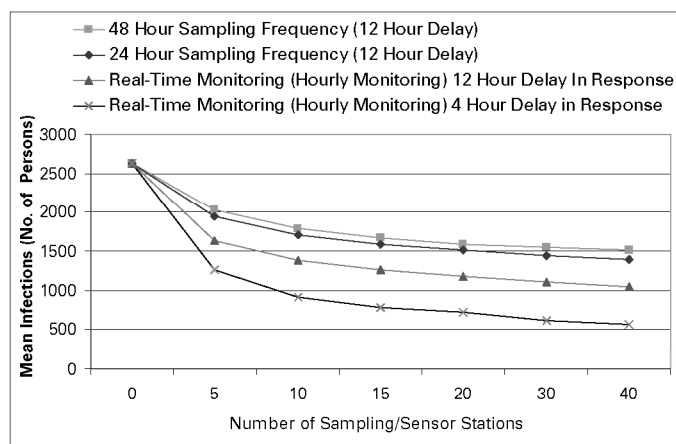


Figure 7-23. Comparison of 24-Hour, 48-Hour, and Real-Time, Continuous Contamination Monitoring Systems for the Reduction in Mean Infections for a 24-Hour Contaminant Attack.

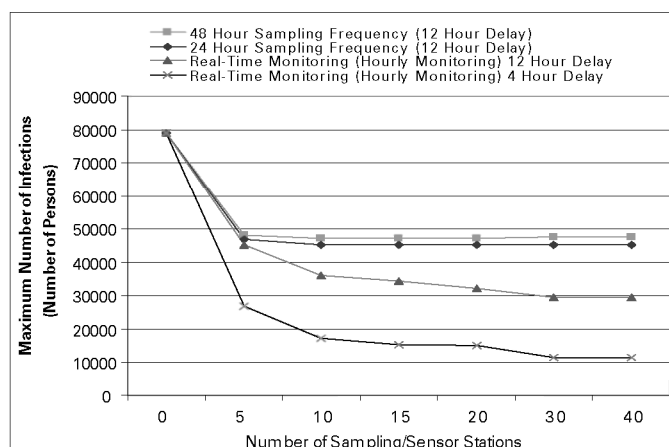


Figure 7-24. Comparison of 24-Hour, 48-Hour, and Real-Time, Continuous Contamination Monitoring Systems for the Reduction in the Maximum Number of Infections for a 24-Hour Contaminant Attack.

than the daily sampling program. Figure 7-23 shows an 80 percent reduction in mean infections is achieved using 40 real-time monitors, as compared to having zero monitors. The results show that it is important that the real-time program be integrated with a response protocol. A comparison of the two real-time, continuous monitoring cases (12-hour delay versus 4-hour delay in notifying the public) illustrates the importance of response time. Shortening the time needed to implement an effective response to reduce further exposure is critical for reducing the number of additional infections.

The results of this case study also illustrate that, for this distribution system, strategically placing just 5 or 10 sampling/sensor stations as part of a monitoring and surveillance system can have a significant effect on reducing potential health impacts from intentional contamination.

7.6.3 Case Summary

TEVA is an integrated system intended to provide the capability for analyzing the vulnerabilities of drinking water distribution systems and to measure the public health and economic impacts. TEVA can be used to design and evaluate threat mitigation and response strategies related to events of intentional introduction of chemical, biological, or radiological contaminants into drinking water networks. Monte-Carlo simulations generate ensembles of threat scenarios to identify vulnerable areas of the water distribution network. TEVA is based on the use of an all pipes EPANET network model.

7.7 Field Testing of Water-Distribution Systems in Support of an Epidemiologic Study

This case study is focused on the use of information collected as part of field studies to assist in the calibration of a hydraulic and water quality model of a distribution system. The information presented in this section is based on an ongoing investigation by the ATSDR at the U.S. Marine Corps Base, Camp Lejeune, NC (Camp Lejeune). These data are being collected to support an ongoing epidemiologic study at Camp Lejeune. The resulting calibrated model is needed to perform a historical reconstruction of the water system for the period of interest. This case study highlights the field methodologies employed to generate the information proposed for use in the calibration of the model.

Key Phrases to Characterize Case Study: field studies, historical reconstruction, hydraulic and water quality modeling, model calibration.

7.7.1 Case Study Overview

ATSDR is conducting an epidemiologic study to determine if there is an association between exposure to contaminated drinking water and birth defects among children of women who lived at Camp Lejeune while they were pregnant between 1968 and 1985. Because of the paucity of historical water distribution system operational data, information based on the operation of present-day water distribution systems will be used for historical reconstruction. Present-day system operations will be modeled using water-distribution system models. To calibrate the models against hydraulic and water quality parameters, field testing is being performed to gather data and information on hydraulic, fate and transport, and operational characteristics of the water distribution systems (Maslia et al., 2005; Sautner et al., 2005). The specific field activities are discussed later in Section 7.7.2.

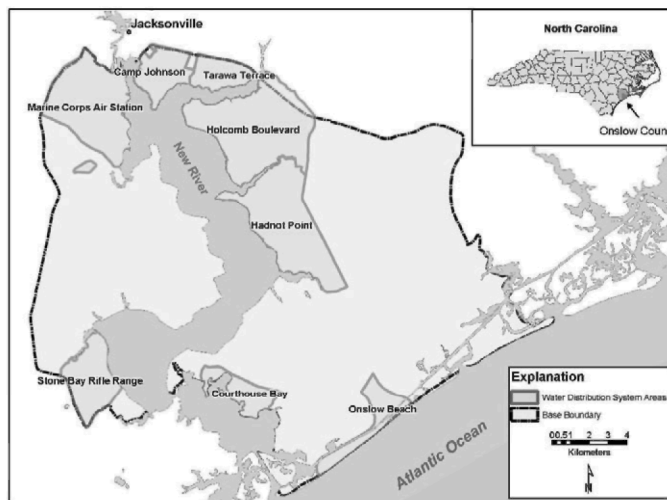


Figure 7-25. Water Distribution Systems Serving U.S. Marine Corps Base, Camp Lejeune, NC.

Camp Lejeune encompasses an area of about 164 square miles, and is located in Jacksonville, Onslow County, North Carolina, bordering the Atlantic Ocean. The focus of the epidemiologic study is on exposure from water-distribution systems that historically served the military base's housing—Camp Johnson, Tarawa Terrace, Holcomb Boulevard, and Hadnot Point (see Figure 7-25). Presently, there are two operating water treatment plants (WTPs) that provide water for the distribution systems of interest to the epidemiologic study: (1) the Holcomb Boulevard WTP that services the Camp Johnson, Tarawa Terrace, and Holcomb Boulevard areas of the distribution system, and (2) the Hadnot Point WTP that services the Hadnot Point area of the distribution system. Hadnot Point was the original WTP and at one time, serviced the entire base. The Holcomb Boulevard WTP presently services the rest of the military housing areas. A third plant, the Tarawa Terrace WTP, historically serviced the Tarawa Terrace and Camp Johnson areas, but this plant was shut down and replaced by a ground storage tank at Tarawa Terrace that receives water directly from the Holcomb Boulevard WTP.

System pressures range from about 55–68 psi throughout the distribution systems. As topography is very flat, ranging from sea level to less than 40 ft, hydraulic heads range from 140–160 ft resulting in a very mild hydraulic gradient. There are nine elevated storage tanks in the Holcomb Boulevard and Hadnot Point WTP service areas. The range in water level fluctuation for the elevated storage tanks is small; generally 1–6 ft. Excellent mapping information and a detailed GIS provide good information on the location and characteristics of the water system facilities. SCADA data are available that provide continuous



Figure 7-26. Continuous Recording Pressure Logger Mounted on Brass Shutoff Valve and Hydrant Adapter Cap Used for Fire-Flow and C-Factor Tests.

information on plant discharges and tank water levels. However, individual buildings and residences are not metered.

7.7.2 Field Work

A variety of field activities are being performed to provide a better understanding of the operation of the water system and to provide information that can be used to calibrate a detailed water distribution system model. To date, these activities have included:

- conducting C-factor and fire-flow tests,
- recording system pressures and storage tank water levels over time,
- tracer and associated travel time tests, and
- recording continuous flow information at key locations.

Several of these field activities were performed in tandem in order to provide an integrated understanding of the system operation and performance.

7.7.2.1 C-Factor and Fire-Flow Tests

C-factor tests and fire-flow tests were conducted in August 2004 at various sites at Camp Lejeune. Continuous pressure loggers (Figure 7-26) set to record pressure at 1-minute intervals were attached to hydrants. Standard analog pressure gages were also used as backup during the tests. Hydrant flows were measured using pitot gages installed on hydrants that were flowed during the tests. One of the pitot gages was integrated with a diffuser and cage to both diffuse the flow from the hydrant and to trap any solids to prevent damage from the flow (see Figure 4-6 in Chapter 4). The other pitot gage was a standard gage attached to the hydrant.

Standard C-factor testing procedures were used to measure data needed to calculate the Hazen-Williams C-factors for eight sections representing a variety of pipe materials and diameters.

Fire-flow tests are frequently used in the process of calibrating a hydraulic water distribution system model. One or more hydrants are opened and flowed to increase flows in the distribution system in the vicinity of the hydrants. Since friction losses increase exponentially, the higher flows can result in a significant lowering of the hydraulic grade line (HGL). In calibrating the model, the model is applied under the flow and operational conditions experienced during the fire-flow test and the pressures or hydraulic grade line observed in the field are compared to the model results. If there are significant differences between the model and field results, adjustments are made in model parameters in order to reduce the differences or calibrate the model. In the simplest configuration, a single hydrant is flowed and pressure read at another single hydrant. An alternative approach was used at Camp Lejeune to improve the labor efficiency and to collect more data. Continuous recording pressure gages were installed at up to six hydrants in the area being tested. Additionally, pitot gages were installed on two hydrants that were designated as hydrants to be flowed. Pressure was measured under several conditions: (1) static conditions at start of testing, (2) while each of the two hydrants was flowed separately, (3) while both hydrants were flowed together, and (4) static conditions at the end of testing. The results of such a test at one site are shown in Figure 7-27 and Table 7-2.

7.7.2.2 Tracer Test and Continuous Measurements

A field test was conducted May 24–27, 2004, in the Hadnot Point (Camp Lejeune) distribution system consisting of three activities: (1) injecting liquid CaCl_2 , 35 percent by weight, into the transmission main on the distribution system side of the WTP to achieve an elevated conductance and chloride concentration, and recording conductivity and chloride concentration using continuous recording



Figure 7-27. Location of Fire Hydrants Used in Fire-Flow Test at Site H02.

Table 7-2. Field Data Collected During Fire-Flow Test at Site H02

	FF-H02-P0 Pressure, Psi	FF-H02-P1 Pressure, Psi	FF-H02-P2 Pressure, Psi	FF-H02-P3 Pressure, Psi	FF-H02-Q1 Flow, gpm	FF-H02-Q2 Flow, gpm
Static case (start)	53.1	50.7	56.2	52.6	0	0
Hydrant 1 flowed	41.4	37.3	46.8	42.9	773	0
Hydrant 1+2 flowed	29.7	24.5	36.5	32.7	631	579
Hydrant 2 flowed	43.9	40.7	48.1	44.1	0	747
Static case (end)	53.5	51.2	56.5	52.9	0	0

1.0 psi = 6.8948 kPa; 1 gpm = 0.0639 L/S

water-quality monitoring data loggers, (2) injecting a sodium fluoride solution into the transmission main to achieve an elevated fluoride concentration and monitoring fluoride concentration in the distribution system, and (3) monitoring distribution system pressures with continuous recording data loggers attached to selected hydrants and flows and tank water levels from SCADA data. In addition to continuously recording tracer concentrations and conductivity, grab samples were collected for quality assurance and quality control (QA/QC) purposes. Samples were analyzed at the Hadnot Point WTP by ATSDR staff and then also shipped to the Federal Occupational Health (FOH) environmental laboratory in Chicago, Illinois, for analysis. Twenty-seven hydrants were selected in the Hadnot Point area as monitoring locations. For monitoring conductivity and chloride and fluoride concentrations, nine hydrants were equipped with the Horiba W-23XD dual probe ion detector (Figure 7-28). For monitoring conductivity, nine hydrants were equipped with the Horiba W-21XD single probe ion detector, thus providing a total of 18 monitoring locations for continuously recording conductivity data. For pressure measurements, nine hydrants were equipped with continuous recording Dixon PR300 pressure data loggers (Figure 7-26).

Results from the chloride injection were used to estimate arrival times of the tracer at different locations throughout the Hadnot Point WTP area. Of special interest are the extremely long arrival times—in excess of 16 hours—in the northwestern part of the of the Hadnot Point WTP area (Figure 7-29, loggers C01, C02, and F01). Additionally, a comparison of arrival times of the calcium chloride tracer at logger location C04 with arrival times at loggers F04, F05, and F02, led investigators to consider that there may have been undocumented

closed valves in the distribution system (the closed valves did not affect C-factor measurements). Post-test field verification by water utility staff confirmed the locations of closed valves, as indicated by the “•” symbol in Figure 7-29.

7.7.3 Additional Test Procedures

A second tracer test was conducted in the Holcomb Boulevard WTP area in September–October 2004. In this test, the normal fluoride feed was turned off for a period of a week and then turned back on and



Figure 7-28. Horiba W-23XD Dual Probe Ion Detector Inside Flow Cell.

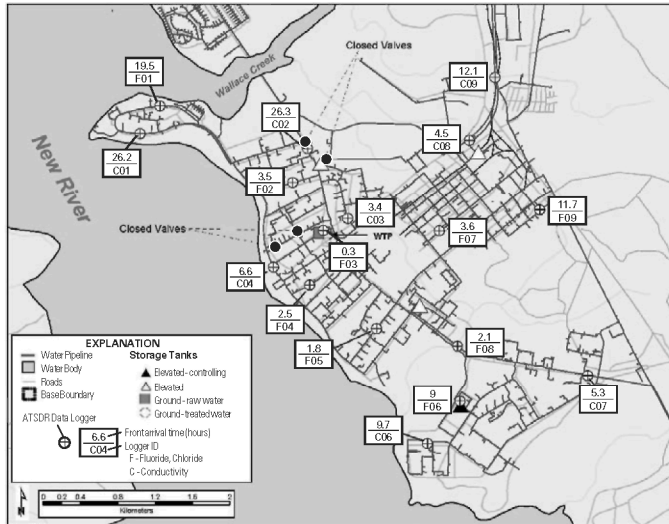


Figure 7-29. Arrival Times of the Calcium Chloride Tracer at Monitoring Locations in Hadnot Point WTP Area, May 25, 2004.

monitored for another week. Nine locations in the distribution system were equipped with the Horiba W-23XD continuous recording, dual probe ion detector data logger. Minimal labor was required in support of this test. Additionally, 16 magnetic flow meters have been installed throughout the system and will be used in conjunction with future tracer tests to provide additional calibration information.

7.7.4 Case Study Summary

This case study presents results from preliminary field-test activities used to gather hydraulic and water quality data at Camp Lejeune. Field tests to date have included: (a) recording system pressures and storage tank water levels, and (b) conducting C-factor, fire-flow, tracer, and travel time tests. The test data are being used to assist with hydraulic and water quality model calibration. They are also being used to plan and carry out a more refined, detailed field test of water distribution systems serving military base housing. These activities will assist in providing much-needed model parameter data for calibrating models of the present-day water distribution system. The present-day models are needed as a first step in reconstructing historical operations during the period between 1968 and 1985, as part of an ongoing epidemiologic study of childhood diseases at Camp Lejeune.

7.8 Chapter Summary

The case studies presented in this chapter illustrate the various ways in which the tools presented in this reference guide can be used. The case studies also demonstrate that, for each application, a specific analysis methodology needs to be developed depending upon the study objectives and available data.

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