

Manual of Water Supply Practices

**M32**

# Computer Modeling of Water Distribution Systems

Fourth Edition



American Water Works  
Association

# Computer Modeling of Water Distribution Systems

Fourth Edition



American Water Works  
Association

Manual of Water Supply Practices—M32, Fourth Edition

## Computer Modeling of Water Distribution Systems

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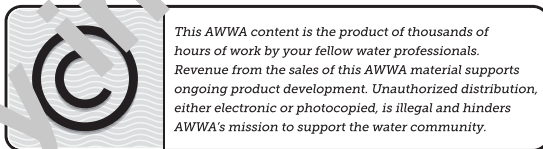
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**American Water Works  
Association**

American Water Works Association  
6666 West Quincy Avenue  
Denver, CO 80235-3098  
[awwa.org](http://awwa.org)

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Chair—James P. Cooper, P.E., *Arcadis, Akron, Ohio*

## Authors

### Chapter 1 Introduction to Distribution System Modeling

*Sharavan V. Govindan*, Bentley Systems Inc., Exton, Penn.

*Adam Simonsen*, IDModeling Inc., Waterbury, Conn.

### Chapter 2 Building and Preparing the Model

*Christie Patel, P.E.*, Brown and Caldwell, Philadelphia, Penn.

*Mike Rosh*, Bentley Systems Inc., Sayre, Penn.

### Chapter 3 Hydraulic Tests and Measurements

*James P. Cooper, P.E.*, Arcadis, Akron, Ohio

*Douglas Lane, P.E.*, City of Bellevue, Bellevue, Wash.

### Chapter 4 Hydraulic Calibration

*Douglas Harrold, P.E.*, City of Santa Clara Water and Sewer Utilities,  
Santa Clara, Calif.

*Saša Tomic', P.E., Ph.D.*, HDR Engineering Inc., New York, N.Y.

### Chapter 5 Steady-State Simulation

*Paul Hsiung, P.E.*, Innovyze, Shawnee Mission, Kans.

*Amanda Schwerman, P.E.*, Black & Veatch, Tampa, Fla.

### Chapter 6 Extended-Period Simulation

*Patrick B. Moore, P.E.*, Innovyze, Edgewood, N.M.

*Lindle D. Willnow, P.E.*, AECOM, Wakefield, Mass.

### Chapter 7 Water Quality Modeling

*James P. Cooper, P.E.*, Arcadis, Akron, Ohio

*Megan G. Roberts, P.E.*, Hazen and Sawyer, P.C., Greensboro, N.C.

### Chapter 8 Storage Tank Mixing and Water Age

*Bob Hawboldt, P.E., Ph.D.*, Associated Engineering, Saskatoon, Sask.

*Ferdous Mahmood, P.E.*, Arcadis, Dallas, Texas

### Chapter 9 Model Maintenance

*Jeff Cowburn*, City of Abbotsford, Abbotsford, B.C.  
*Mike Rosh*, Bentley Systems Inc., Sayre, Penn.  
*Saša Tomic', P.E., Ph.D.*, HDR Engineering Inc., New York, N.Y.

### Chapter 10 Transient Analysis

*Ferdous Mahmood, P.E.*, Arcadis, Dallas, Texas  
*Lindle D. Willnow, P.E.*, AECOM, Wakefield, Mass.

### Chapter 11 Advanced Modeling Applications

*Rajan Ray*, Innovyze, Wakefield, R.I.  
*Adam Simonsen*, IDModeling Inc., Waterbury, Conn.  
*Thomas M. Walski, Ph.D., P.E.*, Bentley Systems Inc., Nanticoke, Penn.

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*Paul F. Boulos, Ph.D.*, Innovyze, Broomfield, Colo.  
*Jeff Cowburn*, City of Abbotsford, Abbotsford, B.C.  
*Nass Diallo, P.E.*, Las Vegas Valley Water District, Las Vegas, Nev.  
*Jerry A. Edwards, P.E.*, Bohannon Huston, Englewood, Colo.  
*Jeff Frey, P.E.*, Optimatics, Chicago, Ill.  
*Walter M. Grayman, P.E., Ph.D.*, W.M. Grayman Consulting Engineer,  
Cincinnati, Ohio  
*Douglas Harrold, P.E.*, City of Santa Clara Water and Sewer Utilities,  
Santa Clara, Calif.  
*Paul M. Hauffen*, IDModeling Inc., Arcadia, Calif.  
*J. Erick Heath, P.E.*, Innovyze, Arcadia, Calif.  
*Jonathan Keck*, California Water Service,  
*Douglas Lane, P.E.*, City of Bellevue, Bellevue, Wash.  
*Patrick B. Moore, P.E.*, Innovyze, Edgewood, NM.  
*Myron Nealey, P.E.*, Denver Water, Denver, Colo.  
*Christie Patel, P.E.*, Brown and Caldwell, Philadelphia, Penn.  
*Theresa O'Grady, P.E.*, Crawford, Murphy & Tilly, Aurora, IL.  
*Rajan Ray*, Innovyze, Wakefield, R.I.  
*Jeffrey Rosenlund*, DOWL, Sheridan, Wyo.  
*Mike Rosh*, Bentley Systems Inc., Sayre, Penn.  
*Amanda Schwerman, P.E.*, Black & Veatch, Tampa, Fla.  
*Jennifer Suttles, P.E.*, Hazen & Sawyer, Atlanta, Ga.  
*Jim Uber*, CitiLogics, Covington, Ky.  
*Bryon Wood, P.E.*, HDR Engineering, Inc., Ann Arbor, Mich  
*Andy Yang*, San Jose Water Company, San Jose, Calif.  
*Samual Ziemann*, C3 Water, Breslau, Ont.  
*Jill Zimmerman*, Albemarle County Service Authority, Charlottesville, Va.

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*James P. Cooper, P.E.*, Arcadis, Akron, Ohio

*Theresa O'Grady, P.E.*, Crawford, Murphy & Tilly, Aurora, Ill.

*Patrick F. Parault, P.E.*, Arcadis, Long Island City, N.Y.

*Jennifer Santini*, American Water Works Association, Denver, Colo.

*Jim Siriano*, American Water Works Association, Denver, Colo.

*Saša Tomic', P.E., Ph.D.*, HDR Engineering Inc., New York, N.Y.

*Thomas M. Walski, Ph.D., P.E.*, Bentley Systems Inc., Nanticoke, Penn.

*Lindle D. Willnow, P.E.*, AECOM, Wakefield, Mass.

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# Introduction to Distribution System Modeling

## 1.1. INTRODUCTION

Water utilities seek to provide customers with a safe, reliable, continuous supply of high-quality drinking water while managing costs. This water is often delivered through a complex network of pipelines, numerous pumps, regulating valves, and storage reservoirs. The performance of these water systems is often difficult to measure and understand because of their physical size, complexity, underground location (out of sight, out of mind), and the large amount of system data needed to fully grasp how they function. Sometimes, key pieces of information needed to understand a system are missing or incomplete. One tool that has evolved over time to help water system designers, operators, planners, and managers meet their goals of delivering a safe, reliable, cost-effective water supply is a water distribution system model (herein referred to as a *model*).

Distribution system modeling (commonly referred to as *hydraulic modeling*) involves the use of a computerized mathematical model to predict the performance of a water system to solve a wide variety of issues including, but not limited to, design, operations, system planning, water quality, water loss, energy management, and emergency response. Models can help water utilities by enabling more proactive and responsive decision making, delivering better customer service, and ensuring employee satisfaction. Water utilities can use models to understand the infrastructure and operations needed to support a network of growing residential and commercial consumers. For example, a model can predict pressures and flows within a water system in order to evaluate a design and compare the system performance against design standards. Models are also used in operational studies to answer questions related to storage capacity, control schemes, water delivery, water

quality, and more. Water quality models are used to predict water age, track disinfectant residuals, and reduce disinfection by-products in a distribution system.

Computerized system modeling began with the advent of analog computers and has evolved as software and hardware have advanced to become more powerful and easier to use. Models that contain hundreds or thousands of miles of pipeline are now common and can be used on a wide variety of computer platforms. Models that once took hours to run are now run in seconds or fractions of a second. Originally, models were used only to evaluate system hydraulic grade lines, system pressures, and flows.

Historically, model building was an expensive and labor-intensive process due to lack of available data to build from and to support relevant applications. Now, models can effectively share data with geographic information systems (GIS), computer-aided design and drafting (CADD) systems, supervisory control and data acquisition (SCADA) systems, customer information systems (CIS), computerized maintenance management systems (CMMS), and asset management system (AMS) software, thus reducing the effort needed to create, update, calibrate, and maintain a model. Information obtained from a model study can be filtered, organized, and presented using a variety of graphical and tabular methods so that results can be more easily understood and communicated. These advances in technology have broadened the uses of distribution system modeling from just an infrastructure planning tool to an integrated design-and-operations analysis system.

## 1.2. PURPOSE OF THIS MANUAL

The Engineering Modeling Applications Committee of the American Water Works Association developed this manual. The purpose of this manual is to share the committee's collective experience with distribution system modeling to help educate and communicate the benefits of a model to water utilities and water customers everywhere.

The manual is intended to be a basic-level or primer reference guide to provide new to intermediate modelers with a foundation for, and practical benefits of, water distribution system modeling. The manual takes users through the modeling process from development to system analysis as shown in Figure 1-1. The manual delivers in-depth discussion on

- Model construction and development,
- Field data collection and testing,
- Model calibration,
- Steady-state analysis,
- Extended-period simulation,
- Water quality analysis,
- Storage tank mixing and water age analysis,
- Model maintenance,
- Transient analysis, and
- Advanced modeling applications.

M32 is designed to help modelers use water models as effective tools to plan, design, and operate a water distribution system; maintain acceptable water quality; and reduce both operating costs and water loss within their water distribution systems.

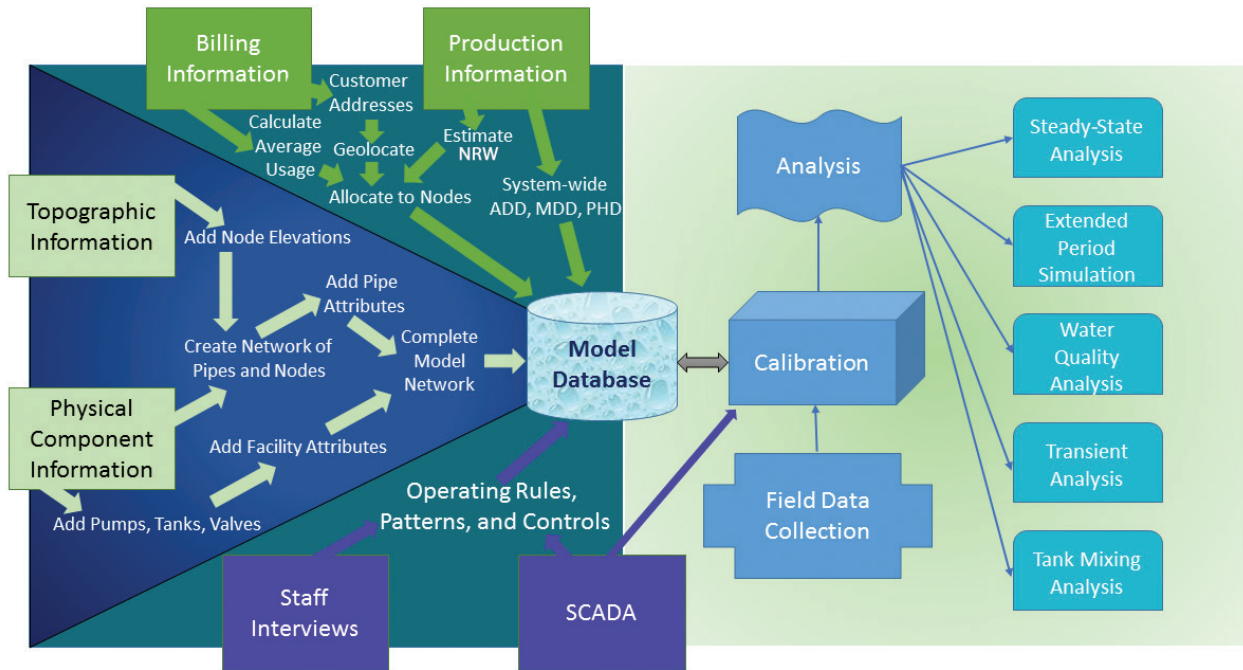


Figure 1-1 Overview of an example modeling process

Abbreviations: ADD (average day demand), MDD (maximum daily demand), PHD (peak hourly demand), SCADA (supervisory control and data acquisition), NRW (non-revenue water).

## 1.3. HISTORICAL DEVELOPMENT OF DISTRIBUTION SYSTEM MODELING

### 1.3.1. Pre-1970

Manual engineering calculations for small-pipe systems were used through the 1960s. The Hardy Cross method was sufficient for single-loop systems. However, without the aid of a computer, this method was impractical for more complex systems with multiple loops. In 1950, McIlroy simulated the behavior of water distribution systems using electronic circuitry. However, these physical models were large, expensive, and difficult to use. In the 1960s, digital computer models appeared, and the FORTRAN programming language was primarily used to develop various models that became available to practicing engineers.

### 1.3.2. 1970–1990

Modeling software was developed with increasing capabilities and more advanced simulations, including extended period simulation and water quality analysis. Graphical user interface capabilities were incorporated to draw the water system and display output. Software packages that contained several compatible modular components were marketed. Some packages used other complementary software for data entry, display, and reporting of results.

### 1.3.3. 1990s

The 1990s experienced exponential growth of distribution system modeling capabilities. EPANET, a water modeling simulation engine and software developed by the US Environmental Protection Agency (USEPA) to support ongoing research, was made available to the public. Some commercial software vendors have taken the EPANET simulation engine

and added an improved user interface and enhanced capabilities. Commercial modeling software was developed to interface with industry-leading CADD and GIS software packages. The result was a familiar user interface and the ability to use existing software and data sources rather than having to create a new water model manually from scratch. Water quality modeling and extended period simulations became standard features in commercially available modeling software packages.

#### **1.3.4. 2000–2010**

Software packages were developed to interface more effectively within GIS software environments in response to the rapid adoption of GIS as the standard database format for assets and asset management. The use of GIS had become more common, and the quality of data had improved, which significantly reduced the effort required to develop models. Automation tools became available for optimizing model development and aiding the calibration process. Security concerns resulted in studies to develop emergency response plans in order to evaluate the potential impacts various disasters might have on water distribution systems. Models were used increasingly for water quality analyses, such as evaluating water age and constituent concentrations. USEPA also allowed use of modeling to determine preferred locations for water quality monitoring sites necessary to meet regulatory requirements.

#### **1.3.5. The Present**

The availability of tremendous amounts of information from various data sources, real-time instrumentation, faster computers, high computer network bandwidth, and well-funded commercial and academic research and development has expanded the uses and applications of models to newer areas. Drought and water scarcity have raised awareness of water loss in distribution systems, and models are being recognized as a tool to identify and manage water leakage detection to reduce nonrevenue water. Climate change, measuring a utility's carbon footprint, and mandatory conservation in some arid regions have increased the importance of operational efficiency and pump energy management, placing a spotlight on the water distribution system model as a means to analyze and optimize a utility's pumping operations. Additionally, transient analysis studies have resulted in the need to design for transient conditions to reduce potential pipe breaks and water contamination. As concern for water quality within water storage reservoirs increases, modeling of these facilities has become more important to ensure proper mixing and to meet more stringent water quality regulations. Unidirectional flushing programs are being developed to enhance system water quality. The use of machine learning, such as genetic algorithms for system optimization and calibration, and other advanced modeling tools are now in frequent use. Water quality and system security planning continue to be critical applications because of increased regulations and national threat levels. Software packages now have the sophistication to perform network calibrations as well as help determine where closed valves exist within the system. Current water models are helping utilities sustain infrastructure in challenging economic times by allowing system owners to quantify and reduce operating hours, water loss, pipe breaks, energy usage, and a host of other related costs.

## 1.4. DISTRIBUTION SYSTEM MODELING APPLICATIONS

### 1.4.1. Benefits of Water Distribution System Modeling

When properly implemented, models become an integral part of the decision-making process for planning, designing, and operating a water distribution system. Water system engineers and operators are ultimately responsible for decisions based on the results that computer models provide.

Distribution system modeling software generally falls into four categories of application: planning, engineering design, system operations, and water quality improvement.

### 1.4.2. Planning

A primary planning application of distribution system analysis software is used for assisting in the development of near- and long-term capital improvement projects, which include scheduling, staging, sizing, and establishing preliminary routing and location of future facilities. Other applications include planning for water main rehabilitation and system improvement. Rehabilitation plans identify and prioritize mains that need to be cleaned and/or lined. Distribution system improvement plans identify where installation of new mains, storage facilities, and pump stations are necessary to keep pace with growth and/or new utility standards and regulations. The following are examples of several specific system analysis planning applications.

**1.4.2.1. Capital Improvement Program.** Water utilities usually develop a master plan that identifies future capital improvements necessary to support projected community growth and to replace aging infrastructure. These plans typically consider planning horizons of 5 to 20 years or more. A model is used to help identify and schedule near- and long-term capital improvements.

**1.4.2.2. Conservation Impact Studies.** Water conservation is desirable for most communities to extend limited water supplies or to reduce water use so that some capital improvements can be delayed or eliminated. A model is useful to predict effects of various conservation measures on future planning periods to evaluate the potential for success.

**1.4.2.3. Water Main Rehabilitation Program.** A model is used to identify specific water mains that tend to bottleneck the system, due either to increased demands or tuberculated pipes. The model is used to determine the potential hydraulic effects of replacing, upsizing, or rehabilitating aging mains to evaluate the effectiveness of various alternatives.

**1.4.2.4. Tank Siting.** A water tank should be sited in a location that optimizes water replenishment, effectively meets peak demands, and can refill efficiently during off-peak demand periods.

### 1.4.3. Engineering Design

Engineering design applications include the sizing of various types of facilities including pipelines, pump stations, control valves, tanks, and reservoirs. These facilities are sized using pressures and flows that result from distribution system modeling. Practical considerations such as accessibility, obstructions, special structures (e.g., hospitals, schools), proximity to alternate water sources, and other circumstances can be factored into system design. In addition, system performance can be analyzed under fire flow conditions and adjustments made to meet fire demand. The following are examples of engineering design problems that can be solved using computer models.

**1.4.3.1. Fire Flow Studies.** The model is used to simulate fire flow demands at hydrant locations throughout a locality to determine how much water can be delivered to specific fire hydrants within the prescribed fire flow requirements. Where deficiencies are discovered, distribution system improvements such as main reinforcements or looping can also be evaluated using the model. These studies are also used to demonstrate compliance with fire protection standards and guidelines.

**1.4.3.2. Control Valve Sizing.** A distribution system often has pressure-regulating or pressure-sustaining valves to direct flow to different hydraulic pressure zones. Distribution systems may also have throttle valves to direct flow within a zone to different reservoirs or storage tank locations. The model is used to determine how much flow is expected through these valves so that the valves are sized appropriately.

**1.4.3.3. Tank Sizing.** Tanks are often sized by estimating the total diurnal flow, fire flow, and emergency storage requirements within a particular zone. However, tank capacity should also consider the rate of water delivery to the tank location and the size of the distribution area. A model is useful to evaluate inflows and outflows to a tank to determine an optimal size for a particular location and/or to specify other improvements so that the preferred tank site is adequately served by transmission mains and pumping stations.

**1.4.3.4. Pump Station/Pump Sizing.** Models are used to calculate system curves of distribution systems so that appropriate pumps are selected to provide the necessary flow and head. Once sized, the proposed pumps are then used in the model under a wide range of system settings to determine how well they perform under various operating conditions.

**1.4.3.5. Estimation of Pressure and Flow at Particular Locations.** A water distribution system must provide adequate amounts of water at appropriate pressures within a range typically specified by standards used in the water industry. Models are used to predict pressures under specific demand conditions and under a wide variety of scenarios to identify low pressures and to select infrastructure that will improve flow or lessen pressure deficiencies. Additionally, hydraulic models are increasingly being used to evaluate transient scenarios and develop capital or operational alternatives to mitigate them.

**1.4.3.6. Zone Boundary Selection.** Most water distribution systems deliver water to customers located at a range of elevations. Such distribution systems are separated into pressure zones that follow consistent elevation contours to keep pressures within reasonable ranges. Models are useful to evaluate potential zone boundaries and to determine the adequacy of infrastructure delivering water to each zone.

#### **1.4.4. System Operations**

Model applications for operations include assisting in the development of operating parameters and strategies, operator training programs, and system troubleshooting guidelines. Emergency conditions, energy management, water availability, and other factors may drive operating strategies. For example, contingency plans are developed in the event of a key facility component failure such as a pump station failure. Distribution system modeling is also used to develop operational strategies for energy management and water quality guidelines. Strategies for shifting supply between treatment plants are developed to determine the most efficient use of available water. Optimizing these strategies results in efficient use of pipeline capacities, tank levels, and required treatment plant production, among other things.

**1.4.4.1. Personnel Training.** Models are used to train personnel who operate the distribution system. System operators can experiment with the model and determine how the system responds to changes in operating parameters and conditions.

**1.4.4.2. Troubleshooting.** Models are used to troubleshoot potential causes of various problems such as low pressure, water circulation issues, and events that would otherwise be inexplicable.

**1.4.4.3. Water Loss Calculations.** In the event of a major main break, the model is used to estimate the amount of water lost through the break, which may be required for damage assessments.

**1.4.4.4. Emergency Operations Scenarios.** Water distribution systems often have critical components; if these components fail, water delivery is interrupted or the level of service is reduced. A model is useful to evaluate the potential impact of a failure and to devise ways to reduce the damage or impact of a critical component failure.

**1.4.4.5. Source and Storage Management.** Water treatment plants and tanks are sometimes taken out of service for repairs or because the water supply is unavailable for a time. In addition, the quality of water at one source may be better at certain times of the year, so the use of the high-quality source can be maximized. The model is useful for devising operating scenarios that best use multiple water sources to achieve desired system objectives.

**1.4.4.6. Model Calibration.** Model calibration is a critical step in developing a useful model. The model results are compared with field measurements, and adjustments are made to the model to improve agreement between the two. However, the calibration process is also useful to operations staff in discovering anomalies in the distribution system, such as closed valves, tuberculated pipes, leaks, or false or incomplete infrastructure data. This information, once discovered through the calibration process, can explain operational difficulties and identify distribution system problems that require the development of solutions to resolve and improve system operation.

**1.4.4.7. Main Flushing Programs.** A model is a useful tool for developing a main flushing program. The model helps identify flow paths in the distribution system so that appropriate flushing locations and sequences can be established. Models are especially useful for developing unidirectional flushing programs.

**1.4.4.8. Outage Areas.** Water utilities frequently need to isolate a specific area of the distribution system for maintenance or other work by taking a pipeline or facility out of service. Often, it is helpful to identify those customers whose service will be interrupted by the outage event. In addition, those planning the event need to know which valves to close in order to minimize impacts of the outage. Models are a valuable tool for accomplishing this task.

**1.4.4.9. Energy Cost Management.** Energy costs associated with pumping typically account for 75 to 80 percent of the power consumed by water utilities. With energy costs being such a high percentage of total operating costs, utilities are trying to find ways to reduce their overall energy consumption. Many current models have features to help quantify energy consumption and costs and to optimize pump operation to reduce electrical usage and take advantage of off-peak energy rates.

### 1.4.5. Water Quality Improvement

Regulations, standards, and expectations for water quality continue to evolve and expand, increasing the demand for water quality analysis. Following are examples of how distribution system modeling is used to improve water quality.

**1.4.5.1. Contaminant Tracing.** If a contaminant enters the distribution system through a treatment plant, well, reservoir, or other location, it can quickly spread throughout the distribution system, affecting the quality of water consumers receive. The contaminated water may also mix with water from other sources. A model can be used to determine the point of entry of the contaminant and to predict contaminant levels and zones of influence within the distribution system. This allows a utility to identify which customers might be affected by the contaminant and the portions of the distribution system that might need to be flushed.

**1.4.5.2. Water Source Tracing.** A model can be used to trace the source of water to any point in the model when multiple sources are present. A source trace analysis provides the percentage of water from each source present. When multiple sources serve an area, distribution system modeling also helps devise operating strategies to reduce water age where possible.

**1.4.5.3. Water Age.** Water age, or hydraulic residence time, is another important water quality parameter in a distribution system, often used as a surrogate for other water quality parameters. Chlorine levels decay over time, increasing the tendency for disinfection by-product (DBP) levels to increase as chlorine reacts with organic compounds in the water and along the pipe wall. To maintain adequate water quality, water utilities strive to minimize water age.

**1.4.5.4. Chlorine Levels.** A model is used to predict chlorine decay in a distribution system. This helps to determine a target level for chlorine entering the distribution system and to select sites where it may be necessary to boost chlorine levels. Other constituent levels can also be predicted with a model. Many models can analyze more than one constituent at a time.

**1.4.5.5. Water Quality Monitoring Locations.** Some water quality regulations under the Safe Drinking Water Act (e.g., DBP rules) require utilities to select sites within a distribution system where they will collect samples to demonstrate compliance. A model can help identify the most appropriate locations for these water quality monitoring locations.

## 1.5. HYDRAULIC MODELS

A model is composed of two parts: a database for the specific water system and a computer program to solve hydraulic and water quality equations. The database contains information that describes the system's infrastructure, demands, and operational characteristics. The computer program solves a set of energy, continuity, transport, or optimization equations to predict pressure flows, tank levels, valve position, pump status, water age, or water chemical concentrations under a variety of scenarios. The computer program also helps create and maintain the database and presents model results in graphical and tabular forms.

## 1.5.1. Model Data

A model consists of two types of elements: links and nodes. Depending on the model, the primary components include pipes, junctions, pumps, tanks, hydrants, and valves that are represented by either a link or a node. Once built, the model database becomes a valuable asset to the user and is the result of substantial effort in data collection, entry, and quality control. A key to maintaining the model's value is making sure it is updated to reflect changes in infrastructure components, system demands, or operating parameters. Creators of models should consider how the model will be maintained over time to ensure continued confidence in the model's results.

## 1.5.2. Modeling Software

**1.5.2.1. Modeling Equations.** At the heart of water distribution system modeling software is a simulation engine that can solve a series of numerical calculations (e.g., hydraulic and water quality equations). Depending on the problem, several kinds of equations are solved.

### 1.5.2.2. Water Model Analysis

**1.5.2.2.1. Steady-State Analyses.** A steady-state analysis provides a snapshot of pipe system conditions at any instant in time. Steady-state analyses are typically used to evaluate maximum day, average day, peak hour, and fire flow conditions.

**1.5.2.2.2. Extended-Period Simulation.** An extended-period simulation is a series of steady-state simulations executed at specified intervals and performed over a specified time period. This capability may be used, for instance, to model the operation of a water system over a 24-hour period. Such a simulation is useful in modeling variations in demand, reservoir operations, water quality, emergency responses, energy management, and water transfers through transmission pipelines. Extended-period simulation requires that the modeling software model flow and pressure variations, incorporate diurnal water demand patterns, simulate operational controls for pumps and control valves, and allow for varying tank configurations.

### 1.5.2.3. Specialized Model Analysis

**1.5.2.3.1. Automated Fire Flow Calculation.** Some distribution system modeling packages automatically calculate the available fire flow at each node. These calculations are useful in identifying areas with weak firefighting capability.

**1.5.2.3.2. Water Quality.** Utilities are increasingly interested in modeling the water quality within a distribution system, particularly the decay of chlorine residual and water age. The ability to perform water quality analysis should be a standard part of any modeling package.

**1.5.2.3.3. Energy Analysis.** Energy analysis, available in most modeling software, can help identify inefficient pumps and determine better operational strategies. Energy costs are a significant portion of the total expense for most utilities. Some electricity providers have variable rates, and electricity costs can vary depending on when pumps are operated. Energy consumption and energy costs can be quantified through this type of analysis.

**1.5.2.3.4. Transient Analysis.** Transient pressures (water hammer or surge) can cause pipe breaks, contamination, joints to shift and leak, collapse of pipes, and other serious damage to water distribution networks. A transient event is caused by a sudden change in flow

velocity that can be created by a valve that is closed too quickly, pump failure or a pump simply shutting down, a mishandled fire hydrant, and similar activities. After identifying a transient condition (valve closure), water-transient analysis software can identify where a transient event is likely to happen and evaluate multiple transient protection devices that can help mitigate or prevent damage.

#### 1.5.2.4. Modeling Software Package Functionality

1.5.2.4.1. *Scenario Generation.* Distribution systems with any level of complexity are modeled more easily by applying various combinations of demands, facilities, and operating parameters, such as regulating-valve and pumping-unit settings. System modeling packages may allow variation and combination of these three types of data in a simulation for specific or combined model access.

1.5.2.4.2. *Selective Reporting of Results.* The user can specify the results to be reported for each simulation. In some cases, a user may only be interested in results from a specific portion of the system. By limiting results to specific portions of the system, the user saves hard disk space and paper while speeding the user's review time.

1.5.2.4.3. *Data Management.* Modelers can export and import data and model results to and from other applications such as spreadsheets, databases, and GIS systems. These capabilities are widely available and are an important part of any modeling package.

### 1.5.3. Related Software Systems

Information management within utilities is moving toward greater information sharing, enabling staff to have appropriate information to make decisions. This is often done by using common databases and files that are shared by a multitude of software applications. Distribution system modeling uses different types of information about physical assets, customers, billing, geographical information, and operational information. Furthermore, modeling results can benefit many groups within the utility, strengthening the ability to communicate and share information. Brief descriptions of software systems, information systems, and/or industry standard databases that are in some way related to distribution system modeling are provided here.

1.5.3.1. **Geographic Information System.** A GIS stores and displays geographically referenced information, that is, information that is easily understood through map display. Spatial relationships between entities are significant for most information stored in GIS. GIS has the potential to store vast amounts of information that is useful for system analysis, including pipe assets, customer meter locations, zoning and land parcel data, aerial photography and other land bases, street locations, digital terrain models (DTMs), digital elevation models (DEMs), and jurisdictional boundaries. Spatial analysis capabilities of a GIS also benefit models for demand allocation, topography extraction, and results presentation, as examples.

GIS has further evolved in the areas of data capacity, structure, integrity, and results presentation. Information in GIS is saved in file formats that most modeling software packages can access. Alternatively, information in a GIS database can be translated into a format that can be imported into the model database. Some GIS land-based information and other data layers can be displayed directly within some modeling packages. The usefulness of GIS pipe data is often dependent on the way the information is collected and stored in the GIS database. GIS data is used to build and/or update models to get a detailed representation of the water distribution network.

**1.5.3.2. Computer-Aided Design and Drafting.** CADD systems are sometimes used to manage maps of water distribution systems, making them a source of pipe information that can be transferred to the model. In addition, CADD systems are useful as a means to display model information and results.

**1.5.3.3. Supervisory Control and Data Acquisition.** SCADA systems are used to remotely monitor and control the operation of tanks, pump stations, valves, and other system infrastructure. They are also useful for collecting data such as pressures, flows, water tank levels, valve positions, pump status and speed, chlorine levels, and other information useful in monitoring the distribution system. This information is collected at regular intervals and stored for extended periods of time. SCADA is a good source of operational information as well as data to calibrate a model. SCADA data are also used to define the starting point for operational analyses; this is done using the data to define boundary conditions entered into the model.

**1.5.3.4. Customer Information System.** CIS is useful for developing water demands based on actual customer water consumption. Typically, average annual water usage and customer rate classes are extracted from CIS and then linked to the model via GIS, modeling, or customized tools. The specifics of how CIS data can be linked to the model are highly dependent on the data and software used by the utility.

**1.5.3.5. Laboratory Information Management System.** Laboratory information management system (LIMS) instruments, protocols, standards, and software are vital for monitoring water quality and ensuring safety and regulatory compliance. Utilities continuously sample water for certain parameters and are expected to accurately report water quality issues immediately. Water models can assist with developing flushing routines, chlorination, tracking contaminants, determining water age, and independently locating the likely source of water quality issues.

**1.5.3.6. Computerized Maintenance Management System.** A computerized maintenance management system (CMMS) can act as an access point to post and retrieve system information and costs for operations, maintenance, and rehabilitation. Typically, a CMMS is used to store asset inventory, condition assessments, parts inventory, preventative maintenance activities, service requests, and work orders, all of which can be linked to the object by location and imported into models for a variety of applications. A pipe's maintenance history can be useful for modeling as it can be related to the pipe's roughness.

**1.5.3.7. Asset Management System.** Similar to CMMS, asset management software is becoming more prevalent as a strategic planning tool for water utilities. This management tool combines long-range planning, life-cycle costing, proactive operations and maintenance, and capital replacement plans based on cost-benefit analyses. These applications are used to meet a wide range of management challenges that water utilities face today. Modeling is an integral part of the long-range decision-making process and can be incorporated into a comprehensive asset management program for achieving system sustainability. AMS seeks to provide informed, timely, and cost-effective decision making for both day-to-day operations and long-term planning.

Many of these systems also enable users to integrate different applications and data sets already in use, including GIS, CMMS, and other work orders as well as modeling/analysis software.