ADVANCED WATER DISTRIBUTION MODELING AND MANAGEMENT

Authors
Thomas M. Walski
Donald V. Chase
Dragan A. Savic
Walter Grayman
Stephen Beckwith
Edmundo Koelle

Contributing Authors
Scott Cattran, Rick Hammond, Kevin Laptos, Steven G. Lowry,
Robert F. Mankowski, Stan Plante, John Przybyla, Barbara Schmitz

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James W. Male (University of Portland), William M. Richards
(WMR Engineering), Zheng Wu (Bentley Systems),
and E. Benjamin Wylie (University of Michigan)

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Introduction to Water Distribution Modeling

Water distribution modeling is the latest technology in a process of advancement that began two millennia ago when the Minoans constructed the first piped water conveyance system. Today, water distribution modeling is a critical part of designing and operating water distribution systems that are capable of serving communities reliably, efficiently, and safely, both now and in the future. The availability of increasingly sophisticated and accessible models allows these goals to be realized more fully than ever before.

This book is structured to take the engineer through the entire modeling process, from gathering system data and understanding how a computer model works, through constructing and calibrating the model, to implementing the model in system design and operations. The text is designed to be a first course for the novice modeler or engineering student, as well as a reference for those more experienced with distribution system simulations.

This chapter introduces the reader to water distribution modeling by giving an overview of the basic distribution system components, defining the nature and purposes of distribution system simulations, and outlining the basic steps in the modeling process. The last section of the chapter presents a chronology of advancements in water distribution.

1.1 ANATOMY OF A WATER DISTRIBUTION SYSTEM

Although the size and complexity of water distribution systems vary dramatically, they all have the same basic purpose—to deliver water from the source (or treatment facility) to the customer.
Sources of Potable Water

Untreated water (also called raw water) may come from groundwater sources or surface waters such as lakes, reservoirs, and rivers. The raw water is usually transported to a water treatment plant, where it is processed to produce treated water (also known as potable or finished water). The degree to which the raw water is processed to achieve potability depends on the characteristics of the raw water, relevant drinking water standards, treatment processes used, and the characteristics of the distribution system.

Before leaving the plant and entering the water distribution system, treated surface water usually enters a unit called a clearwell. The clearwell serves three main purposes in water treatment. First, it provides contact time for disinfectants such as chlorine that are added near the end of the treatment process. Adequate contact time is required to achieve acceptable levels of disinfection.

Second, the clearwell provides storage that acts as a buffer between the treatment plant and the distribution system. Distribution systems naturally fluctuate between periods of high and low water usage, thus the clearwell stores excess treated water during periods of low demand and delivers it during periods of peak demand. Not only does this storage make it possible for the treatment plant to operate at a more stable rate, but it also means that the plant does not need to be designed to handle peak demands. Rather, it can be built to handle more moderate treatment rates, which means lower construction and operational costs.

Third, the clearwell can serve as a source for backwash water for cleaning plant filters that, when needed, is used at a high rate for a short period of time.

In the case of groundwater, many sources offer up consistently high quality water that could be consumed without disinfection. However, the practice of maintaining a disinfectant residual is almost always adhered to for protection against accidental contamination and microbial regrowth in the distribution system. Disinfection at groundwater sources differs from sources influenced by surface water in that it is usually applied at the well itself.

Customers of Potable Water

Customers of a water supply system are easily identified — they are the reason that the system exists in the first place. Homeowners, factories, hospitals, restaurants, golf courses, and thousands of other types of customers depend on water systems to provide everything from safe drinking water to irrigation. As demonstrated throughout the book, customers and the nature in which they use water are the driving mechanism behind how a water distribution system behaves. Water use can vary over time both in the long-term (seasonally) and the short-term (daily), and over space. Good knowledge of how water use is distributed across the system is critical to accurate modeling.

Transport Facilities

Moving water from the source to the customer requires a network of pipes, pumps, valves, and other appurtenances. Storing water to accommodate fluctuations in demand due to varying rates of usage or fire protection needs requires storage facili-
ties such as tanks and reservoirs. Piping, storage, and the supporting infrastructure are together referred to as the water distribution system (WDS).

**Transmission and Distribution Mains.** This system of piping is often categorized into transmission/trunk mains and distribution mains. Transmission mains consist of components that are designed to convey large amounts of water over great distances, typically between major facilities within the system. For example, a transmission main may be used to transport water from a treatment facility to storage tanks throughout several cities and towns. Individual customers are usually not served from transmission mains.

Distribution mains are an intermediate step toward delivering water to the end customers. Distribution mains are smaller in diameter than transmission mains, and typically follow the general topology and alignment of the city streets. Elbows, tees, wyes, crosses, and numerous other fittings are used to connect and redirect sections of pipe. Fire hydrants, isolation valves, control valves, blow-offs, and other maintenance and operational appurtenances are frequently connected directly to the distribution mains. Services, also called service lines, transmit the water from the distribution mains to the end customers.

Homes, businesses, and industries have their own internal plumbing systems to transport water to sinks, washing machines, hose bibbs, and so forth. Typically, the internal plumbing of a customer is not included in a WDS model; however, in some cases, such as sprinkler systems, internal plumbing may be modeled.

**System Configurations.** Transmission and distribution systems can be either looped or branched, as shown in Figure 1.1. As the name suggests, in looped systems there may be several different paths that the water can follow to get from the source to a particular customer. In a branched system, also called a tree or dendritic system, the water has only one possible path from the source to a customer.

**Figure 1.1**
Looped and branched networks
Looped systems are generally more desirable than branched systems because, coupled with sufficient valving, they can provide an additional level of reliability. For example, consider a main break occurring near the reservoir in each system depicted in Figure 1.2. In the looped system, that break can be isolated and repaired with little impact on customers outside of that immediate area. In the branched system, however, all the customers downstream from the break will have their water service interrupted until the repairs are finished. Another advantage of a looped configuration is that, because there is more than one path for water to reach the user, the velocities will be lower, and system capacity greater.

**Figure 1.2**
Looped and branched networks after network failure

Most water supply systems are a complex combination of loops and branches, with a trade-off between loops for reliability (redundancy) and branches for infrastructure cost savings. In systems such as rural distribution networks, the low density of customers may make interconnecting the branches of the system prohibitive from both monetary and logistical standpoints.

### 1.2 WHAT IS A WATER DISTRIBUTION SYSTEM SIMULATION?

The term *simulation* generally refers to the process of imitating the behavior of one system through the functions of another. In this book, the term *simulation* refers to the process of using a mathematical representation of the real system, called a *model*. Network simulations, which replicate the dynamics of an existing or proposed system, are commonly performed when it is not practical for the real system to be directly subjected to experimentation, or for the purpose of evaluating a system before it is actually built. In addition, for situations in which water quality is an issue, directly testing a system may be costly and a potentially hazardous risk to public health.
Simulations can be used to predict system responses to events under a wide range of conditions without disrupting the actual system. Using simulations, problems can be anticipated in proposed or existing systems, and solutions can be evaluated before time, money, and materials are invested in a real-world project.

For example, a water utility might want to verify that a new subdivision can be provided with enough water to fight a fire without compromising the level of service to existing customers. The system could be built and tested directly, but if any problems were to be discovered, the cost of correction would be enormous. Regardless of project size, model-based simulation can provide valuable information to assist an engineer in making well-informed decisions.

Simulations can either be steady-state or extended-period. Steady-state simulations represent a snapshot in time and are used to determine the operating behavior of a system under static conditions. This type of analysis can be useful in determining the short-term effect of fire flows or average demand conditions on the system. Extended-period simulations (EPS) are used to evaluate system performance over time. This type of analysis allows the user to model tanks filling and draining, regulating valves opening and closing, and pressures and flow rates changing throughout the system in response to varying demand conditions and automatic control strategies formulated by the modeler.

Modern simulation software packages use a graphical user interface (GUI) that makes it easier to create models and visualize the results of simulations. Older-generation software relied exclusively on tabular input and output. A typical modern software interface with an annotated model drawing is shown in Figure 1.3.
1.3 APPLICATIONS OF WATER DISTRIBUTION MODELS

Most water distribution models (WDMs) can be used to analyze a variety of other pressure piping systems, such as industrial cooling systems, oil pipelines, or any network carrying an incompressible, single-phase, Newtonian fluid in full pipes. Municipal water utilities, however, are by far the most common application of these models. Models are especially important for WDSs due to their complex topology, frequent growth and change, and sheer size. It is not uncommon for a system to supply hundreds of thousands of people (large networks supply millions); thus, the potential impact of a utility decision can be tremendous.

Water distribution network simulations are used for a variety of purposes, such as:

- Long-range master planning, including both new development and rehabilitation
- Fire protection studies
- Water quality investigations
- Energy management
- System design
- Daily operational uses including operator training, emergency response, and troubleshooting

Long-Range Master Planning

Planners carefully research all aspects of a water distribution system and try to determine which major capital improvement projects are necessary to ensure the quality of service for the future. This process, called master planning (also referred to as capital improvement planning or comprehensive planning), may be used to project system growth and water usage for the next 5, 10, or 20 years. System growth may occur because of population growth, annexation, acquisition, or wholesale agreements between water supply utilities. The capability of the hydraulic network to adequately serve its customers must be evaluated whenever system growth is anticipated.

Not only can a model be used to identify potential problem areas (such as future low pressure areas or areas with water quality problems), but it can also be used to size and locate new transmission mains, pumping stations, and storage facilities to ensure that the predicted problems never occur. Maintaining a system at an acceptable level of service is preferable to having to rehabilitate a system that has become problematic.

Rehabilitation

As with all engineered systems, the wear and tear on a water distribution system may lead to the eventual need to rehabilitate portions of the system such as pipes, pumps, valves, and reservoirs. Pipes, especially older, unlined, metal pipes, may experience an internal buildup of deposits due to mineral deposits and chemical reactions within the water. This buildup can result in loss of carrying capacity, reduced pressures, and
poorer water quality. To counter these effects of aging, a utility may choose to clean and reline a pipe. Alternatively, the pipe may be replaced with a new (possibly larger) pipe, or another pipe may be installed in parallel. Hydraulic simulations can be used to assess the impacts of such rehabilitation efforts, and to determine the most economical improvements.

**Fire Protection Studies**

Water distribution systems are often required to provide water for fire fighting purposes. Designing the system to meet the fire protection requirements is essential and normally has a large impact on the design of the entire network. The engineer determines the fire protection requirements and then uses a model to test whether the system can meet those requirements. If the system cannot provide certain flows and maintain adequate pressures, the model may also be used for sizing hydraulic elements (pipes, pumps, etc.) to correct the problem.

**Water Quality Investigations**

Some models provide *water quality modeling* in addition to hydraulic simulation capabilities. Using a water quality model, the user can model water age, source tracing, and constituent concentration analyses throughout a network. For example, chlorine residual maintenance can be studied and planned more effectively, *disinfection by-product formation* (DBP) in a network can be analyzed, or the impact of storage tanks on water quality can be evaluated. Water quality models are also used to study the modification of hydraulic operations to improve water quality.

**Energy Management**

Next to infrastructure maintenance and repair costs, energy usage for pumping is the largest operating expense of many water utilities (Figure 1.4). Hydraulic simulations can be used to study the operating characteristics and energy usage of pumps, along with the behavior of the system. By developing and testing different pumping strategies, the effects on energy consumption can be evaluated, and the utility can make an educated effort to save on energy costs.

**Daily Operations**

Individuals who operate water distribution systems are generally responsible for making sure that system-wide pressures, flows, and tank water levels remain within acceptable limits. The operator must monitor these indicators and take action when a value falls outside the acceptable range. By turning on a pump or adjusting a valve, for example, the operator can adjust the system so that it functions at an appropriate level of service. A hydraulic simulation can be used in daily operations to determine the impact of various possible actions, providing the operator with better information for decision-making.
Pumping is one of the largest operating expenses of many utilities.

**Operator Training.** Most water distribution system operators do their jobs very well. As testimony to this fact, the majority of systems experience very few water outages, and those that do occur are rarely caused by operator error. Many operators, however, gain experience and confidence in their ability to operate the system only over a long period of time, and sometimes the most critical experience is gained under conditions of extreme duress. Hydraulic simulations offer an excellent opportunity to train system operators in how their system will behave under different loading conditions, with various control strategies, and in emergency situations.

**Emergency Response.** Emergencies are a very real part of operating a water distribution system, and operators need to be prepared to handle everything from main breaks to power failures. Planning ahead for these emergencies by using a model may prevent service from being compromised, or may at least minimize the extent to which customers are affected. Modeling is an excellent tool for emergency response planning and contingency.

**System Troubleshooting.** When hydraulic or water quality characteristics in an existing system are not up to standard, a model simulation can be used to identify probable causes. A series of simulations for a neighborhood that suffers from chronic low pressure, for example, may point toward the likelihood of a closed valve in the area. A field crew can then be dispatched to this area to check nearby valves.

**1.4 THE MODELING PROCESS**

Assembling, calibrating, and using a water distribution system model can seem like a foreboding task to someone confronted with a new program and stacks of data and maps of the actual system. As with any large task, the way to complete it is to break it down into its components and work through each step. Some tasks can be done in parallel while others must be done in series. The tasks that make up the modeling process are illustrated in Figure 1.5. Note that modeling is an iterative process.
Figure 1.5
Flowchart of the modeling process
The first step in undertaking any modeling project is to develop a consensus within the water utility regarding the need for the model and the purposes for which the model will be used in both the short- and long-term. It is important to have utility personnel, from upper management and engineering to operations and maintenance, commit to the model in terms of human resources, time, and funding. Modeling should not be viewed as an isolated endeavor by a single modeler, but rather a utility-wide effort with the modeler as the key worker. After the vision of the model has been accepted by the utility, decisions on such issues as extent of model skeletonization and accuracy of calibration will naturally follow.

Figure 1.5 shows that most of the work in modeling must be done before the model can be used to solve real problems. Therefore, it is important to budget sufficient time to use the model once it has been developed and calibrated. Too many modeling projects fall short of their goals for usage because the model-building process takes up all of the allotted time and resources. There is not enough time left to use the model to understand the full range of alternative solutions to the problems.

Modeling involves a series of abstractions. First, the real pipes and pumps in the system are represented in maps and drawings of those facilities. Then, the maps are converted to a model that represents the facilities as links and nodes. Another layer of abstraction is introduced as the behaviors of the links and nodes are described mathematically. The model equations are then solved, and the solutions are typically displayed on maps of the system or as tabular output. A model’s value stems from the usefulness of these abstractions in facilitating efficient design of system improvements or better operation of an existing system.

1.5 A BRIEF HISTORY OF WATER DISTRIBUTION TECHNOLOGY

The practice of transporting water for human consumption has been around for several millennia. From the first pipes in Crete some 3,500 years ago, to today’s complex hydraulic models, the history of water distribution technology is quite a story. The following highlights some of the key historical events that have shaped the field since its beginnings.

1500 B.C. — First water distribution pipes used in Crete. The Minoan civilization flourishes on the island of Crete. The City of Knossos develops an aqueduct system that uses tubular conduits to convey water. Other ancient civilizations have had surface water canals, but these are probably the first pipes.

250 B.C. — Archimedes principle developed. Archimedes, best known for his discovery of π and for devising exponents, develops one of the earliest laws of fluids when he notices that any object in water displaces its own volume. Using this principle, he proves that a crown belonging to King Hiero of Syracuse is not made of gold. A legend will develop that he discovered this principle while bathing and became so excited that he ran naked through the streets shouting “Eureka” (I’ve found it).

100 A.D. — Roman aqueducts. The Romans bring water from great distances to their cities through aqueducts (Figure 1.6). While many of the aqueducts are above-
ground, there are also enclosed conduits to supply public fountains and baths. Sextus Julius Frontinus, water commissioner of Rome, writes two books on the Roman water supply.

1455 — First cast iron pipe. Casting of iron for pipe becomes practical, and the first installation of cast iron pipe, manufactured in Siegerland, Germany, occurs at Dillenburg Castle.

1652 — Piped water in Boston. The first water pipes in the U.S. are laid in Boston to bring water from springs to what is now the Quincy Market area.

1664 — Palace of Versailles. King Louis XIV of France orders the construction of a 15-mile cast iron water main from Marly-on-Seine to the Palace of Versailles. This is the longest pipeline of its kind at this time, and portions of it remain in service into the 21st century. A section of the line, after being taken out of service, was shipped in the 1960s from France to the United States (Figure 1.7) where it is still on display.
1732 — **Pitot invents a velocity-measuring device.** Henri Pitot is tasked with measuring the velocity of water in the Seine River. He finds that by placing an L-shaped tube into the flow, water rises in the tube proportionally to the velocity squared, and the Pitot tube is born.

1738 — **Bernoulli publishes *Hydrodynamica***. The Swiss Bernoulli family extends the early mathematics and physics discoveries of Newton and Leibniz to fluid systems. Daniel Bernoulli publishes *Hydrodynamica* while in St. Petersburg and Strasbourg, but there is a rivalry with his father Johann regarding who actually developed some of the principles presented in the book. These principles will become the key to energy principles used in hydraulic models and the basis for numerous devices such as the Venturi meter and, most notably, the airplane wing. In 1752, however, it will actually be their colleague, Leonard Euler, who develops the forms of the energy equations that will live on in years to come.

1754 — **First U.S. water systems built.** The earliest water distribution systems in the United States are constructed in Pennsylvania. The Moravian community in Bethlehem, Pennsylvania claims to have the first water system, and it is followed quickly by systems in Schaefferstown and Philadelphia, Pennsylvania. Horses drive the pumps in the Philadelphia system, and the pipes are made of bored logs. They will later be replaced with wood stave pipes made with iron hoops to withstand higher pressures. The first steam driven pumps will be used in Bethlehem ten years later.

1770 — **Chezy develops head loss relationship.** While previous investigators realized that energy was lost in moving water, it is Antoine Chezy who realizes that $V^2/RS$ is reasonably constant for certain situations. This relationship will serve as the basis for head loss equations to be used for centuries.

1785 — **Bell and spigot joint developed.** The Chelsea Water Company in London begins using the first bell and spigot joints. The joint is first packed with yarn or hemp and is then sealed with lead. Sir Thomas Simpson is credited with inventing this joint, which replaced the crude flanged joints used previously.

1839 — **Hagen-Poiseuille equation developed.** Gotthilf Hagen and Jean Louis Poiseuille independently develop the head loss equations for laminar flow in small tubes. Their work is experimental, and it is not until 1856 that Franz Neuman and Eduard Hagenbach will theoretically derive the Hagen-Poiseuille equation.

1843 — **St. Venant develops equations of motion.** Several researchers, including Louis Navier, George Stokes, Augustin de Cauchy, and Simeon Poisson, work toward the development of the fundamental differential equations describing the motion of fluids. They become known as the “Navier-Stokes equations.” Jean-Claude Barre de Saint Venant develops the most general form of these equations, but the term *St. Venant equations* will be used to refer to the vertically and laterally averaged (that is, one-dimensional flow) form of equations.

1845 — **Darcy-Weisbach head loss equation developed.** Julius Weisbach publishes a three-volume set on engineering mechanics that includes the results of his experiments. The Darcy-Weisbach equation comes from this work, which is essentially an extension of Chezy’s work, as Chezy’s $C$ is related to Darcy-Weisbach’s $f$ by $C^2=8g/f$. 
Darcy’s name is also associated with Darcy’s law for flow through porous media, widely used in groundwater analysis.

1878 — **First automatic sprinklers used.** The first Parmelee sprinklers are installed. These are the first automatic sprinklers for fire protection.

1879 — **Lamb’s Hydrodynamics published.** Sir Horace Lamb publishes his *Treatise on the Mathematical Theory of the Motion of Fluids*. Subsequent editions will be published under the title *Hydrodynamics*, with the last edition published in 1932.

1881 — **AWWA formed.** The 22 original members create the American Water Works Association. The first president is Jacob Foster from Illinois.

1883 — **Laminar/turbulent flow distinction explained.** While earlier engineers such as Hagen observed the differences between laminar and turbulent flow, Osborne Reynolds is the first to conduct the experiments that clearly define the two flow regimes. He identifies the dimensionless number, later referred to as the Reynolds number, for quantifying the conditions under which each type of flow exists. He publishes “An Experimental Investigation of the Circumstances which Determine whether the Motion of Water shall be Direct or Sinuous and the Law of Resistance in Parallel Channels.”

1896 — **Cole invents Pitot tube for pressure pipe.** Although numerous attempts were made to extend Henri Pitot’s velocity measuring device to pressure pipes, Edward Cole develops the first practical apparatus using a Pitot tube with two tips connected to a manometer. The Cole Pitometer will be widely used for years to come, and Cole’s company, Pitometer Associates, will perform flow measurement studies (among many other services) into the 21st century.

1900 – 1930 — **Boundary Layer Theory developed.** The interactions between fluids and solids are studied extensively by a series of German scientists lead by Ludwig Prandtl and his students Theodor von Karman, Johan Nikuradse, Heinrich Blasius, and Thomas Stanton. As a result of their research, they are able to theoretically explain and experimentally verify the nature of drag between pipe walls and a fluid. In particular, the experiments of Nikuradse, who glues uniform sand grains inside pipes and measures head loss, lead to a better understanding of the calculation of the $f$ coefficient in the Darcy-Weisbach equation. Stanton develops the first graphical representation of the relationship between $f$, pipe roughness, and the Reynolds number, which later leads to the Moody diagram. This work is summarized in H. Schlichting’s book, *Boundary Layer Theory*.

1914 — **First U.S. drinking water standards established.** The U.S. Public Health Service publishes the first drinking water standards, which will continually evolve. The U.S. Environmental Protection Agency (U.S. EPA) will eventually assume the role of setting the water quality standards in the United States.
**1920s — Cement-mortar lining of water mains.** Cement mortar lining of water mains is used to minimize corrosion and tuberculation. Procedures for cleaning and lining existing pipes in place will be developed by the 1930s.

**1921 — First Hydraulic Institute Standards published.** The first edition of *Trade Standards in the Pump Industry* is published as a 19-page pamphlet. These standards become the primary reference for pump nomenclature, testing, and rating.

**1936 — Hardy Cross method developed.** Hardy Cross, a structural engineering professor at the University of Illinois, publishes the Hardy Cross method for solving head loss equations in complex networks. This method is widely used for manual calculations and will serve as the basis for early digital computer programs for pipe network analysis.

**1938 — Colebrook-White equation developed.** Cyril Colebrook and Cedric White of Imperial College in London build upon the work of Prandtl and his students to develop the Colebrook-White equation for determining the Darcy-Weisbach $f$ in commercial pipes.

**1940 — Hunter curves published.** During the 1920s and '30s, Roy Hunter of the National Bureau of Standards conducts research on water use in a variety of buildings. His “fixture unit method” will become the basis for estimating building water use, even though plumbing fixtures will change over the years. His probabilistic analysis captured the mathematics of the concept that the more fixtures in a building, the less likely they are to be used simultaneously.

**1944 — Moody diagram published.** Lewis Moody of Princeton University publishes the Moody diagram, which is essentially a graphical representation of the Colebrook-White equation in the turbulent flow range and the Hagen-Poiseuille equation in the laminar range. This diagram is especially useful because, at the time, no explicit solution exists for the Colebrook-White equation. Stanton had developed a similar chart 30 years earlier.

**1950 — McIlroy network analyzer developed.** The McIlroy network analyzer, an electrical analog computer, is developed to simulate the behavior of water distribution systems using electricity instead of water. The analyzer uses special elements called “fluistors” to reproduce head loss in pipes, because in the Hazen-Williams equation, head loss varies with flow raised to the 1.85 power, while normal resistors comply with Ohm’s law, in which voltage drop varies linearly with current.

**1950s — Earliest digital computers developed.** The Electronic Numerical Integrator and Computer (ENIAC) is assembled at the University of Pennsylvania. It contains approximately 18,000 vacuum tubes and fills a 30 x 50 ft (9 x 15 m) room. Digital computers such as the ENIAC and Univac show that computers can carry out numerical calculations quickly, opening the door for programs to solve complex hydraulic problems.

**1956 — Push-on joint developed.** The push-on pipe joint using a rubber gasket is developed. This type of assembly helps speed the construction of piping.

**1960s and '70s — Earliest pipe network digital models created.** With the coming of age of digital computers and the establishment of the FORTRAN programming
language, researchers at universities begin to develop pipe network models and make them available to practicing engineers. Don Wood at the University of Kentucky, Al Fowler at the University of British Columbia, Roland Jeppson of Utah State University, Chuck Howard and Uri Shamir at MIT, and Simsek Sarikelle at the University of Akron all write pipe network models.

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**1963 — URISA is founded.** The Urban and Regional Information Systems Association is founded by Dr. Edgar Horwood. URISA becomes the premier organization for the use and integration of spatial information technology to improve the quality of life in urban and regional environments.

**1960s and ’70s — Water system contamination.** Chemicals that can result in health problems when ingested or inhaled are dumped on the ground or stored in leaky ponds because of lack of awareness of their environmental impacts. Over the years, these chemicals will make their way into water distribution systems and lead to alleged contamination of water systems in places like Woburn, Massachusetts; Phoenix/Scottsdale, Arizona; and Dover Township, New Jersey. Water quality models of distribution systems will be used to attempt to recreate the dosages of chemicals received by customers. These situations lead to popular movies like *A Civil Action* and *Erin Brockovich*.

**1970s — Early attempts to optimize water distribution design.** Dennis Lai and John Schaake at MIT develop the first approach to optimize water system design. Numerous papers will follow by researchers such as Arun Deb, Ian Goulter, Uri Shamir, Downey Brill, Larry Mays, and Kevin Lansey.

**1970s — Models become more powerful.** Although the earliest pipe network models could only solve steady-state equations for simple systems, the ’70s bring modeling features such as pressure regulating valves and extended-period simulations.
1975 — Data files replace input cards. Modelers are able to remotely create data files on time-share terminals instead of using punched cards.

1975 — AWWA C-900 approved. The AWWA approves its first standard for PVC water distribution piping. C900 pipe is made to match old cast iron pipe outer diameters.

1976 — Swamee-Jain equation published. Dozens of approximations to the Colebrook-White equations have been published in an attempt to arrive at an explicit equation that would give the same results without the need for an iterative solution. Indian engineers P. K. Swamee and Akalnank Jain publish the most popular form of these approximations. The use of an explicit equation results in faster numerical solutions of pipe network problems.

1976 — Jeppson publishes *Analysis of Flow in Pipe Networks*. Roland Jeppson authors the book *Analysis of Flow in Pipe Networks*, which presents a summary of the numerical techniques used to solve network problems.

1980 — Personal computers introduced. Early personal computers make it possible to move hydraulic analysis to desktop systems. Initially, these desktop models are slow, but their power will grow exponentially over the next two decades.

Figure 1.9
Time-share terminal

Early 1980s — Water Quality Modeling First Developed. The concept of modeling water quality in distribution systems is first developed, and steady state formulations are proposed by Don Wood at the University of Kentucky and USEPA researchers in Cincinnati, Ohio.
1985 — “Battle of the Network Models.” A series of sessions is held at the ASCE Water Resources Planning and Management Division Conference in Buffalo, New York, where researchers are given a realistic system called “Anytown” and are asked to optimize the design of that network. Comparison of results shows the strengths and weaknesses of the various models.

1986 — Introduction of Dynamic Water Quality Models. At the AWWA Distribution System Symposium, three groups independently introduce dynamic water quality models of distribution systems.


1989 — AWWA holds specialty conference. AWWA holds the Computers and Automation in the Water Industry conference. This conference will later grow into the popular IMTech event (Information Management and Technology).

1990s — Privatization of water utilities. The privatization of water utilities increases significantly as other utilities experience a greater push toward deregulation.

1991 — Water Quality Modeling in Distribution Systems Conference. The USEPA and the AWWA Research Foundation bring together researchers from around

“Your history, Leonard.”
the world for a two-day meeting in Cincinnati. This meeting is a milestone in the establishment of water quality modeling as a recognized tool for investigators.

1991 — **GPS technology becomes affordable.** The cost of global positioning systems (GPS) drops to the point where a GPS can be an economical tool for determining coordinates of points in hydraulic models.

1993 — **Introduction of water quality modeling tool.** Water quality modeling comes of age with the development of EPANET by Lewis Rossman of the USEPA. Intended as a research tool, EPANET provides the basis for several commercial-grade models.

1990 through present. Several commercial software developers release water distribution modeling packages. Each release brings new enhancements for data management and new abilities to interoperate with other existing computer systems.

2001 — **Automated calibration.** Automated calibration of distribution models moves from being a research tool to a standard modeling feature with the use of Genetic Algorithms.

2001 — **Security awareness.** Water system security increases in importance and utilities realize the value of water quality modeling as a tool for protecting a water system.

2002 — **Integration with GIS.** Water modeling and GIS software become highly integrated with the release of WaterGEMS, software that combines the functionality of both tools.

**What Next?**

Predicting the future is difficult, especially with rapidly changing fields such as the software industry. However, there are definite trends as data sharing continues to gain popularity, modeling spreads into operations, and automated design tools add to the modeler’s arsenal.

The next logical question is, “When will network models eliminate the need for engineers?” The answer is, never. Though a word processor can reduce the number of spelling and grammar mistakes, it cannot write a best-selling novel. Even as technology advances, an essential need still exists for living, breathing, thinking human beings. A network model is just another tool (albeit a very powerful, multi-purpose tool) for an experienced engineer or technician. It is still the responsibility of the user to understand the real system, understand the model, and make decisions based on sound engineering judgement.

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