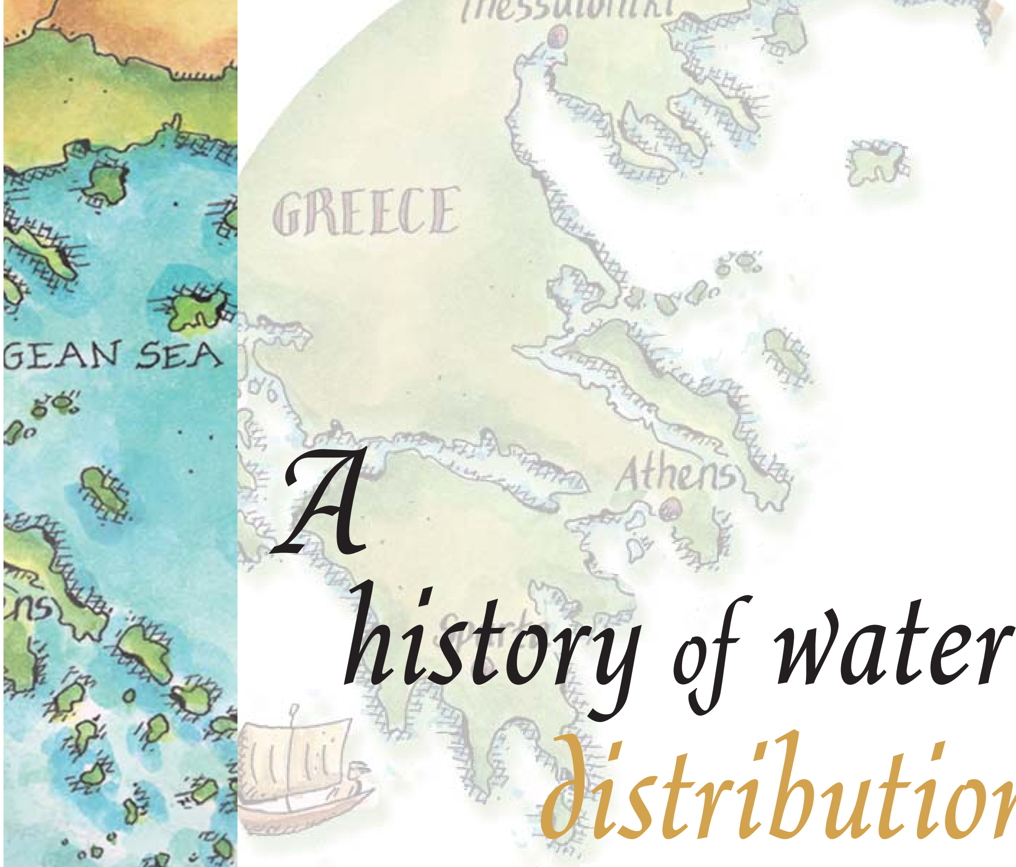


A history of water distribution

Thomas M. Walski

Today, water utility customers take it for granted that they can turn on their faucets and that clean water with adequate pressure will be delivered to them through a water distribution system. Throughout much of human history, however, this convenience has not been available. It took a large number of incremental advances in science and technology to make modern water distribution systems as reliable and inexpensive as they are today.

Early history

Early humans had to carry their water from the source to the point of consumption. With such an effort required, only minimal water for drinking and washing was available. The large volumes of water that we use today for showering, toilet flushing, firefighting, and irrigation could not be delivered manually.

Crouch (1993) reported that the earliest piped water supply dated back to two millennia before the time of Christ. Remnants of pipes were discovered in Minoan cities on the Mediterranean island of Crete, and those systems supplied water through roughly 1400 B.C. Some of the sewers in Crete still function today.

Cities such as Ephesus and Perge in Asia Minor (modern-day Turkey) had functioning water systems centuries before the time of Christ (Mays, 2000). Most pipes in those days were made of clay.

There are reports of early screw pumps, invented by Archimedes of Syracuse, being used in the first century B.C. (Oldfather, 1933). The pumps were used for irrigation and for removing water from the holds of ships (but not for drinking water).

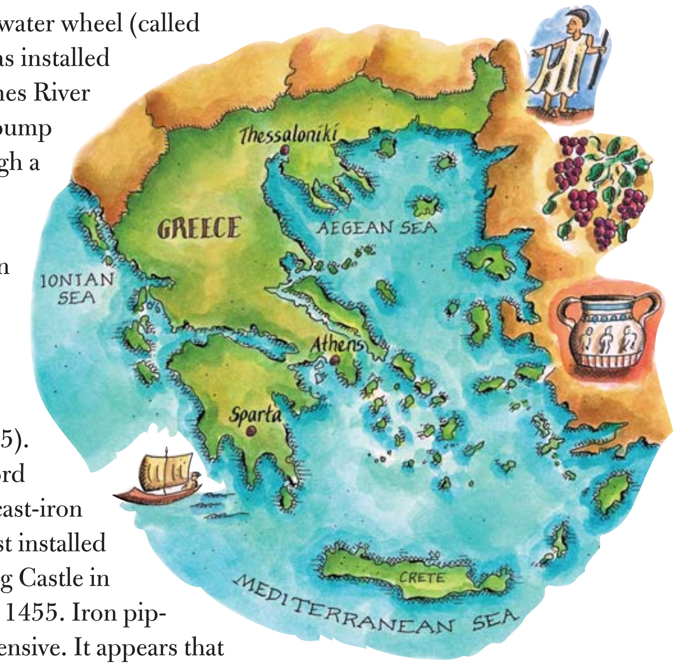
The most extensive water distribution systems in ancient times were the Roman aqueducts, which conveyed water long distances by means of gravity through a collection of open and closed conduits. The first aqueduct was built in 312 B.C., and several more were added over the centuries (Sanks, 2005). The Romans also introduced lead pressure pipes. The word plumber comes from the Latin word for lead, *plumbium.*

After the fall of the Roman Empire—during the Dark Ages—the technology for delivering water deteriorated, and sanitation became poorer than it had been in Roman times (Mays, 2000). It wasn't until after the Renaissance that the technology to deliver water began to evolve once more.

"While complex water distribution systems were not common in the middle ages, systems of channels were constructed to move water from the well sources in and out of castles. Some of these channels which were called 'leats' in England are still in existence today" (Robins, 1946).

Transition to modern times

In the 13th century, a 5.5-km lead pipeline was installed in the United Kingdom to convey water from Tybourne Brook to London. Several similar pipes were later constructed, but service was only provided to a central point in London, and residents had to carry water to their homes in buckets (Sanks, 2005).



A crude water wheel (called a forcier) was installed in the Thames River in 1582 to pump water through a portion of London. It was driven by the flow of water in the Thames (Sanks, 2005).

The record shows that cast-iron pipe was first installed at Dillenburg Castle in Germany in 1455. Iron piping was expensive. It appears that the first major pipeline was a 25-km line from Marly-on-Seine in France to the Palace of Versailles, which was completed in 1664. Early cast-iron pipe used flanged joints, which are no longer used for buried pipe (Walski et al, 2003). The bell-and-spigot joint with poured lead was not developed until 1785 (DIPRA, 2003).

By the mid-1700s, London had more than 50 km of water mains that had been constructed out of a mixture of wood, cast-iron, and lead pipe (Sanks, 2005).

After the fall of the Roman Empire—during the Dark Ages—the technology for delivering water deteriorated, and sanitation became poorer than it had been in Roman times.

Most early small-diameter pipes were made of bored wood logs and had bell-and-spigot joints made of lead. For larger pipes, wood-stave pipe (made of narrow strips of wood) was used. Sanks (2005) reports that wood-stave pipe was used in some places through the early 1900s. Wood pipe remains strong as long as it is kept full of water, and some wood pipes are still in service today.

During the 1800s, cast-iron pipe gradually replaced wooden pipe. The first cast-iron pipes were laid in the United States in Philadelphia, Pa., in 1817. Wrought-iron pipe was also used in the 1800s. San Fran-

PHOTO: AMERICAN CAST IRON

PHOTO: MARY EVANS/PHOTO RESEARCHERS, INC.

Pipe being installed in Conway, Ark., in 1914. The line replaced a wood pipeline that had been installed in 1910.

The science of hydraulics did not advance much until Leonardo da Vinci's treatise "Del moto e misura dell'acqua" summarized the state of the art of hydraulics circa 1500 (Rouse & Ince, 1980).

cisco, Calif., had nearly 125 km of wrought-iron pipe by 1892 (Sanks, 2005).

A pipe was used to bring water to the Quincy Market area of Boston, Mass., in 1652. Records indicate the first water systems in the United States were in Schaefferstown, Pa., in 1746 and in the Moravian settlement that is now Bethlehem, Pa., in 1754 (Mays, 2000). In these systems, bored logs were used for pipes. In roughly the same period, Philadelphia constructed the first system with pumping (using horse-powered pumps).

The science of hydraulics

In early history, there was no formal field of hydraulics, but numerous scientists contributed to the understanding of fluid flow. One of the most notable was Archimedes, who reported on the principles of buoyancy and is credited with developing the screw pump—although his pump was a refinement of earlier designs (Rouse & Ince, 1980). Hero of Alexandria's book, *On the Dioptra,* is the earliest expression of the relationship of velocity, area, and flow (Rouse & Ince, 1980).

Sextus Julius Frontinus is credited with writing the first hydraulics books in 97 A.D., which described the construction of Rome's water supply system. Roman engineering, however, was based more on rules of thumb than on scientific principles.

The science of hydraulics did not advance much until the time of Leonardo da Vinci, when his treatise *Del moto e misura dell'acqua* summarized the state of the art of hydraulics circa 1500 (Rouse & Ince, 1980).

By the early 17th century, Benedetto Castelli had formulated what we now use as the continuity principle. His student Evangelista Torricelli showed that there is a relationship between the velocity of a fluid and the square root of the head (Rouse & Ince, 1980).

Early in the 18th century, Isaac Newton developed the basic laws of motion, which served as the basis for subsequent understandings of hydraulics. In addition to his laws of motion, he developed his law of viscosity, which states that shear resistance is proportional to the velocity gradient.

In the mid-18th century, Daniel Bernoulli and his father Johann developed many of the principles for analyzing fluid flow, and Daniel is credited with publishing the book *Hydrodynamica,* which was the most complete hydraulics book of its time. The equation attributed to Bernoulli (and many of the other basic equations of hydraulics) was actually developed by Leonhard Euler in the mid-1700s (Rouse & Ince, 1980).

In the early 1700s, Henri de Pitot showed that the velocity of a fluid is proportional to the square root of the head. While investigators realized that it took energy to move fluids, Antoine Chezy was the first to extend this idea to show that head loss in a fluid is proportional to the velocity squared. All subsequent head loss equations in turbulent flow are related to his work (Walski et al, 2003).

By 1840, Gotthilf Hagen and Jean Louis Poiseuille were able to develop an analytical equation for predicting head loss in laminar flow. This work and Chezy's equation were extended to a more general formula by Julius Weisbach and Henry Darcy circa 1845 (Rouse & Ince, 1980).

Other head loss equations, more applicable to open-channel rather than closed-pipe flow, were developed by Henri Bazin and Wilhelm Kutter in the early 19th century and by Robert Manning in the late 19th century (Rouse & Ince, 1980).

In 1883, Osborne Reynolds investigated the different flow regimes and was able to clearly define the distinction between laminar and turbulent flow. He also identified the dimensionless number, which is used to characterize the different types of flow.

Although the Darcy–Weisbach equation could be used to determine head loss in pipes, determining the friction factor was difficult. G.S. Williams and Allen Hazen (1906) developed an equation for head loss in smooth turbulent flow with a *C*-factor instead of the friction factor. Because the *C*-factor is significantly more constant and easier to use, widespread use of the Hazen–Williams equation followed.

It was the German "rocket scientists" in the early 20th century who developed a more thorough understanding of the relationships between solid bodies and moving fluids. Ludwig Prandtl and his associates Theodor von Karmen, Johan Nikuradse, Heinrich Blasius, and Thomas Stanton determined that it was the nature of the boundary layer between the fluid and solid phases that determines drag (and head loss). Nikuradse developed the famous experiments in which uniform sand grains were glued to the insides of pipes and head loss was then measured for various velocities. These relationships are summarized in diagrams by Stanton, Hunter Rouse, and (later) Lewis Moody; they show the relationships among the Reynolds number, pipe roughness, and friction factor (Walski et al, 2003).

Although there was a general awareness of hydraulic transients before 1897, it was in that year that Nicolai Joukowsky first demonstrated both theoretically and experimentally the acoustic nature of water hammer resulting from valve closure. He also presented an equation that related the magnitude of transient pressure to the change in velocity (Rouse & Ince, 1980).

Piping

Most older water mains in North America are made of cast iron. Originally, cast iron was cast vertically in pits, but this type of iron was replaced by centrifugally spun cast iron in the 1920s. By the 1930s, bell-and-spigot pipe joints made from poured lead were being replaced by mechanical joints—and later by roll-on and then push-on joints. Today, a wide variety of joints in addition to push-on joints is available, including flanged, ball and socket, and restrained joints (DIPRA, 2003).

This section of wooden pipe originally part of the Seattle Water Department's distribution system, now resides at AWWA headquarters as part of a display of water industry and association artifacts.

The first use of cement–mortar lining of pipes took place in Charleston, S.C., in 1922. To help prevent internal corrosion, cement–mortar lining of cast-iron pipes had become standard practice by the 1940s.

Ductile-iron pipe was first used in 1948, and it has since replaced cast iron in new installations. Ductile-iron pipe has greater tensile strength at less weight than cast-iron pipe. The Cast Iron Pipe Research Association changed its name to the Ductile Iron Pipe Research Association in 1979 (DIPRA, 2003).

Polyethylene encasement of iron pipes was first developed in 1951 to mitigate the effects of corrosive soils on metal pipes. The first standard for polyethylene encasement was approved in 1972 as AWWA C105 (DIPRA, 2003).

Steel pipe can be manufactured in diameters ranging from less than an inch to several feet. Steel pipe, which has been used since the 19th century, can be butt- or spiral-welded (in older pipe it was riveted). Today, it is primarily used in large transmission mains, although some galvanized-steel piping is used in smaller sizes.

Concrete cylinder pipe has been used for water distribution since the 1940s. Concrete cylinder pipe was originally referred to as pretensioned pipe, but it is now referred to as bar-wrapped pipe. This type of pipe has generally been used only for large-diameter transmission mains.

Wood pipe remains strong as long as it is kept full of water, and some wood pipes are still in service today.

PHOTO: COURTESY OF PENNSYLVANIA AMERICAN WATER

Workers install a main in the suburban South Hills of Pittsburgh, Pa., circa the 1950s.

Polyvinyl chloride (PVC) pipe is widely used today in new installations. It was first developed in Germany in the 1930s, and it was introduced in the United States in the 1950s. The use of PVC pipe became more widely accepted as new standards were developed in 1972 to make it compatible with standard iron pipe diameters. AWWA Standard C-900 for PVC pipe was approved in 1976 (Uni-Bell, 2001).

Asbestos–cement (AC) pipe was widely used in the 20th century, especially in smaller diameter pipes. Because of health concerns (especially regarding its manufacture), it is not widely used currently. Although asbestos is considered carcinogenic if inhaled, ingestion of water passing through AC pipe is not considered to be a significant health risk (FWR, 2002).

It took a large number of incremental advances in science and technology to make modern water distribution systems as reliable and inexpensive as they are today.

Service lines were once constructed of lead or copper. Lead is no longer allowed in drinking water piping materials, and most utilities have replaced their lead service lines. Currently, service lines are made of copper or any one of several plastics.

Water mains can lose carrying capacity because of an internal buildup of scale or tuberculation. Early methods of rehabilitating pipe involved cleaning it with a scraper and then adding a cement mortar lining to the pipes. Cleaning pipes using polyurethane “pigs” was introduced later. Newer methods of rehabilitation include slip lining and fold-and-form lining (which involve pulling a smaller pipe inside the old pipe) and pipe bursting (in which old pipe is burst and then a new pipe is pulled through the remaining cavity).

Pumps

Early water systems were primarily gravity fed. The earliest pumps relied on the principles of an Archimedes screw. Pumps in more modern water distribution systems were generally steam-driven positive-displacement pumps.

“Chicago installed one of the first steam-driven pumping systems in the mid-1860s. The pumps fed Chicago's famous water tower, which was constructed in 1869 and is still standing.” (Armstrong, 1976).

During the early 20th century, these pumps were gradually replaced by centrifugal pumps driven by electric motors. Chicago installed its first electric centrifugal pumps in 1910 (Sanks, 2005).

The Hydraulic Institute (originally formed as the Hydraulic Society in 1917) published its first set of standards, *Trade Standards of the Pump Industry,* in 1921. Over the years, pumps have become smaller and run at higher speeds. The major advance that has occurred in recent years has been the development of variable frequency drives to control pump speed more efficiently.

Fire protection

A fire hydrant is the most visible feature of most water distribution systems. In the early days of firefighting, firefighters would dig down to the wooden water main and drill a hole in the pipe. The pipe would fill with water, and the firefighters would pump the water onto the fire. After the fire was extinguished, a plug would be inserted into the pipe. Thus, the term fireplug is still used in some places to describe fire hydrants.

Some of the earliest work on the hydraulics of nozzles and fittings was performed by John

Freeman in the late 1800s (Rouse & Ince, 1980). The first automatic fire sprinklers were developed by Henry Parmalee in 1874. The National Fire Sprinkler Association (originally called the National Automatic Sprinkler and Fire Control Association) was formed in 1914. The National Fire Protection Association published its first *Fire Protection Handbook* in 1896 (NFPA, 2003)

Early hydrants were custom-made for each utility, and it was not until well into the 20th century that outlet size and thread pattern were standardized. In North America, hydrants are generally located aboveground, but in some European countries, hydrants can be belowground and covered by a lid.

Before 1965, fire protection systems in the United States were evaluated by the National Board of Fire Underwriters. However, changes in the insurance industry caused the board to be replaced in 1965 by the American Insurance Association. In 1971 Insurance Services Office Inc. was formed and carries on the responsibility of water system evaluation for the property insurance industry in the United States using its *Fire Suppression Rating Schedule.*

Metering

Henri Pitot developed the first device for measuring fluid velocity in 1730. In 1875, Hiram Mills became the first to use the pitot gauge to measure the discharge from a fire hydrant. However, pitot gauges could not be used in closed pipes until the pitometer was developed by John and Edward Cole in 1895 (Walski et al, 2003).

The first displacement meter for measuring customer water consumption using reciprocating pistons was developed by William Sewell in 1850. The first commercially available meters were made by Henry Worthington—they were $^{5}/_{8}$-in. meters that weighed 57 lbs (AWWA, 1986).

J.A. Tilden received the first patent for a disc meter in 1892, and a conical disc meter was sold by G.A. Bassett in that same year (AWWA, 1986). Gears for these meters needed to be covered with oil. This inconvenience was eliminated with the development of the magnetic drive meter in the late 1950s.

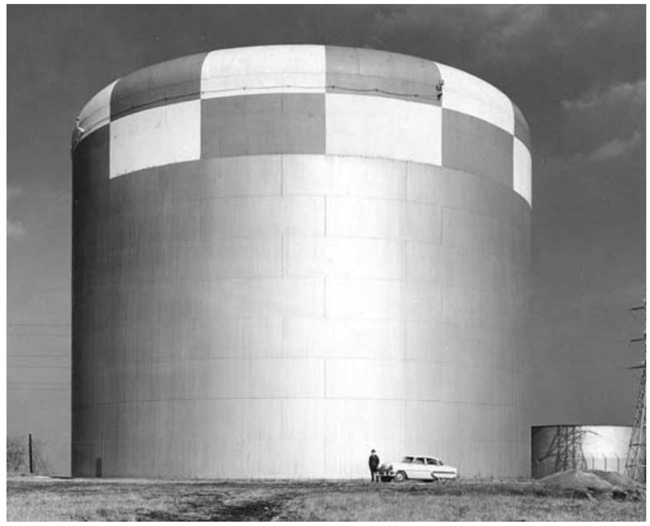


PHOTO: COURTESY OF PENNSYLVANIA AMERICAN WATER

This 1950s photo shows the West Mifflin (Pa.) water tank in suburban Pittsburgh, with its distinctive checkerboard top. The pattern alerts planes flying into the nearby Allegheny County airport to the tank's presence. The majority of aboveground tanks today are steel, and the earliest tanks were constructed of riveted plates.

The first current meter was developed by Reinhard Woltman in Germany in the late 1700s. Siemens & Halske began production of the first closed-pipe current meters in 1865. The first meters that resembled modern turbine meters were called torrent meters and were first used in 1895. The first compound meter, which contained a low-flow displacement meter and a high-flow turbine unit, was patented by J.A. Tilden in 1903 (AWWA, 1986).

It appears that the first major pipeline was a 25-km line from Marly-on-Seine in France to the Palace of Versailles, which was completed in 1664.

Even though Venturi meters are named after an Italian scientist from the early 1800s, the first practical Venturi meter was developed by Clemens Herschel in Massachusetts in the late 1800s. Herschel is also credited with translating the works of Frontinus from Latin to English (Rouse & Ince, 1980).

Most customer meters are totalizing meters and do not provide information on rate of consumption. However, Frank Brainard invented a device in 1931 that recorded rate-of-flow information as well as total flow.

Tanks

Storage tanks are another highly visible component of water systems. The majority of aboveground tanks today are steel, and the earliest tanks were constructed of riveted plates. The first AWWA standard that included welded tanks was published in 1935; by the 1950s, newer technology had replaced constructing tanks with rivets (AWWA, 1998). Bolted tanks with factory coatings have been available since the 1970s and are often used in situations that call for smaller tanks.

Elevated tank design has evolved over the years from multicolumn design to a pedestal design. Improved coatings, cathodic protection systems, and better inspection techniques have led to modern tank coatings with increased life spans.

Concrete is used for underground tanks and some tanks at ground level. J.M. Crom developed the first successful prestressed concrete tank in 1942. A steel diaphragm, serving as both a water barrier and a vertical reinforcment, was first used inside concrete tanks in 1952; by the 1960s, this method had become common practice (ACI, 2003).

Water quality considerations

Throughout much of the history of water distribution, it was assumed that if the water entering the system was of adequate quality, then the water emerging from the tap would also be of acceptable quality. Research eventually showed that water quality could deteriorate in distribution systems because of cross-connections, the growth of biofilms, open water tanks, or the deterioration of distribution system components.

The rules changed in the United States with the passage of the Safe Drinking Water Act in 1974 and its subsequent amendments in 1986 and 1996. The primary change brought about by the new law was the fact that water quality standards now had to be met at the tap.

The new regulations had an impact in such areas as backflow prevention rules, the stability of water in order to prevent lead and copper contamination, the removal of lead from water systems, the monitoring of disinfectant residuals and disinfectant by-product formation, and the covering or abandoning of old open storage tanks. Despite the new regulations, serious contamination events have since occurred in such places as the towns of Cabool and Gideon in Missouri (Clark & Grayman, 1998). In addition, the threat of intentional contamination has become an increasingly important consideration after terrorist attacks in New York City and Washington, D.C., in 2001.

Hydraulic analysis

Solving for flows and pressures in a real water distribution system involves solving thousands of simultaneous nonlinear equations. Until recent advances in computer modeling were achieved, such calculations were impossible. Nevertheless, engineers throughout the early 20th century were able to design and analyze the hydraulics of a functioning water distribution system using a combination of simplifications, rules-of-thumb, and conservatism. The ability of engineers to construct systems exceeded the profession's ability to analyze them.

Freeman developed a graphical method for solving problems with parallel pipes in the late 1800s, and equivalent pipe methods were used to decompose complex problems in the early 1900s (Ramalingam et al, 2002). Nevertheless, looped systems required tedious iterative systems and heavy use of slide rules.

Hardy Cross (1936) at the University of Illinois developed a systematic tabular process for calculating system hydraulics. Although this codified the iterative procedures, the calculations still involved extensive slide rule use. Camp (1943) summarized the state-of-the-art of manual hydraulic analysis for networks and noted that better field data were more important than theoretical calculations.

The first computer solutions of network problems were done on analog computers, with electrical elements being used to simulate pipe networks. The McIlroy Network Analyzer was used by utilities from the early 1950s through the early 1970s to simulate water flow (Walski et al, 2003).

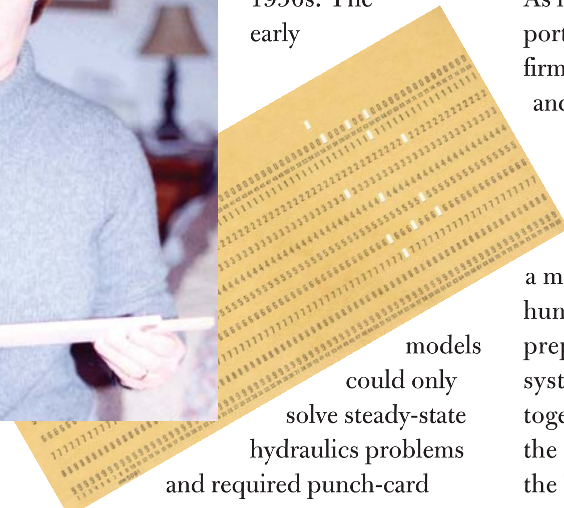


PHOTO: THOMAS M. WALSKI

In the mid-1930s a systematic tabular process for calculating system hydraulics was developed. Although this codified the iterative procedures, the calculations still involved extensive slide rule use. Digital computers were first used to solve network problems in the 1960s. The early models could only solve steady-state hydraulics problems and required punch card input (behind photo) on large mainframe computers.

Digital computers were first used to solve network problems in the early 1950s. The early models could only solve steady-state hydraulics problems and required punch-card input on large mainframe computers. The first model was developed by L.N. Hoag and G. Weinberg for Palo Alto, Calif. (Ramalingam et al, 2002). By 1957, two consulting companies—Rader & Associates and Brown and Caldwell—had developed models, and Datics Corporation was selling a commercial program (*Engineering News–Record,* 1957).

Early hydraulic analysis methods were based on computerizing the Hardy–Cross method, whereas later methods took advantage of the computer's ability to solve matrix problems. Martin and Peters (1963) developed the first matrix solution method. Later models were developed at such universities as the University of Kentucky, Utah State University, the University of British Columbia, and the University of Akron.

These models were later extended to handle more complex hydraulics and included pumps, control valves, and extended-period analysis. Government agencies such as the US Army Corps of Engineers and the US Environmental Protection Agency (USEPA) also developed their own pipe network analysis software. Transient analysis software development followed a path similar to that for network analysis models.

After the fall of the Roman Empire—during the Dark Ages—the technology for delivering water deteriorated, and sanitation became poorer than it had been in Roman times.

The use of hydraulic analysis models spread with the advent of desktop computers. As larger numbers of new users needed support, software development shifted to private firms that could provide technical support and value-added features.

Simulation software could determine flows and pressures but could not select optimal pipe sizes. Optimal design of water distribution systems is a mathematically difficult problem, and hundreds of papers and reports have been prepared that discuss various methods for system optimization. Researchers came together to compare optimization models at the Battle of the Network Models held at the Water Resources Planning and Management Division Conference sponsored by the American Society of Civil Engineers in Buffalo, N.Y., in 1985 (Walski et al, 1987). The researchers were given a water distribution design problem and were asked to solve it with various optimization approaches. The problem is still used as a benchmark today.

Water quality modeling was introduced in the 1980s. A key meeting in 1991, sponsored by USEPA and AWWA, brought together investigators in water quality modeling and led to USEPA's development of a distribution water quality model (Rossman, 2000).

Recent advances in hydraulic analysis have focused on the integration of modeling with geospatial data sources. This has made it less difficult for modelers to create extremely precise, detailed models with a minimum of manual labor, and data can now be shared easily with other parties across the water utility.

Other computer applications

Although hydraulic analysis of pipe networks was the first use (and one of the most prevalent) of computers in water distribution, numerous other applications have evolved since computers came onto the scene.

Supervisory control and data acquisition (SCADA) systems have changed the way operators interact with remote facilities. SCADA systems can link with programmable logic controllers and remote telemetry units at distant facilities to more efficiently operate systems and to diagnose and solve distribution system problems before they become serious. Coupled with advances in data-logging equipment, SCADA systems can now provide operators a much better picture of what is occurring in their systems.

Most utilities had paper-based work order systems in place before computers came into use, but computerized work order management systems—which are often associated with automated mapping and facility management—have enabled utilities to better track work and materials. Having this information available in a digital database enables managers to better operate their systems.

Nikuradse developed the famous experiments in which uniform sand grains were glued to the insides of pipes and head loss was then measured for various velocities.

Until recently, reading water meters had been a tedious manual process. Improvements in automated meter reading technology are bringing it into the realm of being cost-effective for many utilities.

Water distribution system mapping has evolved from pen-and-ink drawings on linen, paper, and Mylar® to digital drawings on computer-assisted design and geospatial information systems. Mapping has evolved from the communication paradigm, in which the end product is a paper map, to the analytical paradigm, in which the end product is a digital model of the distribution system and any map is just one view of that geospatial model.

Use of geospatial technology enables utilities to combine the functionality of mapping and database systems. In such systems, a line on a map is not simply a vector line—it is also a spatial model of a pipe with attributes such as diameter, material, and the year installed. This database may be linked back to a maintenance management system or to hydraulic analysis programs.

Linking systems for maintenance management, mapping, and asset inventory in order to help make better decisions in the areas of infrastructure planning and operations is now referred to collectively as asset management.

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The growth of the Internet has made the sharing of water distribution system information much easier within utilities—as well as among utilities and their suppliers and regulators.

Future trends

Although the future undoubtedly holds many surprises, some current trends can be expected to continue:

- a better understanding of water quality transformations in pipes,
- more emphasis on energy efficiency as energy prices rise,
- incorporation of water security considerations into all design and operation decisions,
- better sharing of information among computer applications as asset management becomes more widely incorporated into decision-making,
- wider use of automated meter reading,
- increased application of point-of-use treatment to overcome water quality problems in distribution systems, and
- more emphasis on rehabilitation and maintenance of existing water distribution infrastructure (as opposed to new construction)

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