WATER TRANSPORT

R. L. Sanks
Professor Emeritus, Department of Civil Engineering, Montana State University, USA

Keywords: Aqueducts, dams, metering, tunneling, pumps, water treatment.

Contents

Summary

This paper and the articles that follow present both a general discussion of the subject, water transport, and some of the details of the various facilities required to accomplish that goal. The brief history given in this paper provides a perspective of water transport as practiced by the ancients from the dawn of civilization and changed but little until the industrial revolution made iron available in great quantity for pipe and machinery. The knowledge of the agents that cause disease, the means to eliminate those agents in public water supplies, the pumps and piping to bring fresh, pure water to every household, to carry wastewater away from every household, and the facilities to protect the environment from domestic and industrial wastes were all discovered or developed in the explosive half-century centered around 1885.

Canals are much the same today as in ancient Sumeria. Tunnels are now bored hundreds of times faster than in the days of the Caesars. Pipe, once made only of lead, clay, or bored logs, is now made from cast iron, steel, reinforced concrete, and plastic in

diameters from a few millimeters to several meters. Moreover, they now supply the humblest citizen whereas in olden times only the kings or the very wealthy could afford piped water.

Where our forebears were limited to water lifters, we now have a wide variety of pumps to suit every purpose from pumping from a well 300 m deep to pumping to a water tower 30 m high, or to pump wastewater to a treatment plant many kilometers distant. (There are even pumps that develop so much pressure that the water jet cuts thick steel.) Before the 18th century, water measurement was unknown, but now most households have water meters used for assessing cost, and there are accurate meters for every flow rate and size of conduit.

Beyond cisterns for storing rain or low dams for storing spring runoff, the ancients would probably have thought little about saving water. Today, there is a thriving effort to conserve precipitation and to reclaim wastewater for industrial purposes such as cooling towers, irrigating park lands, and even for direct reuse.

1. Introduction

Of all of the life support systems that exist, an adequate supply of safe, potable water and the safe collection, treatment, and return of wastes to the environment is the most—or certainly among the most—important to the well-being of a community. The transportation of water and wastes is an important aspect of keeping water supplies safe as well as sequestering wastes until treatment. Many kinds of facilities are required for water (and wastewater) transport. The objective in this topic is to provide a general overview of water transport systems with examples and limited references to some of the most appropriate literature.

Before the 1900s, a large percentage of the population was periodically devastated by salmonellosis, typhoid, and cholera. Scarcely a family existed that did not experience a death from a waterborne disease. More recently, E-coli outbreaks have occurred in California, Ontario, and Michigan. In modern times, carcinogens have appeared in some water supplies. Treatment of water, first by filtration, later by disinfection, and still later by sorption on activated carbon as well as other site-specific processes has, however, virtually eliminated water as a source of disease. The treatment of wastes and their safe return to rivers, lakes, and—to some degree oceans—has provided the planet with a healthy environment everywhere such practices are maintained.

2. A Glimpse into History

Our hunter-gatherer forbears had no need for water works. They simply camped beside their source of water. For most of our existence on earth, water has been delivered to the point of use in jars or bags of animal skins—a practice still followed by some peoples. As population increased, however, and people settled into communities, the need for public supplies and irrigation drove the inhabitants to construct canals, pipelines, and even dams and tunnels. Some of these works are surprisingly ancient.

2.1. Eastern Mediterranean

Minoan technologies (3000 to 1000 B.C.) were so advanced in construction and operation of water and wastewater facilities in Crete as to compare with Europe and North America in the 1850's. Water was transported in sophisticated hydraulic systems over long distances to cities and palaces equipped with bathrooms, bathtubs, flush toilets, and carefully planned and executed sewer projects. The sewers were made of stone blocks and lined with cement. Toilet seats were carved in stone. The villa of Hagia Triadha, near the south coast of Crete, has an advanced system of sewers still functioning perfectly 4000 years after construction. Evidently, the Minoans were superb artisans, energetic, prosperous, and innovative. How many of the works built today will still be functioning in 4000 years? Minoan technologies were exported to Greece as early as the Mycenaean period (2800 to1100 B.C.)

One of the oldest works (ca 2800 B.C.) was the pipelines in ancient Sumeria, the stone collars of which still exist. Egyptians built the first known dam of masonry 15 m (meters) high on the Nile River to supply water to the capitol at Memphis in 2900 B.C. Assyrians, Babylonians and Persians built dams from 700 to 250 B.C. for public water supply and irrigation. Many earthen dams were built in the 5th century B.C. in Ceylon. A large stone crib dam, constructed about 240 B.C. in China, was 30 m high and 300 m long.

The great Assyrian aqueduct, built under Sennacherib about 690 B.C., brought water from the Greater Zab River to the ancient city of Nineveh in northern Iraq, 80 km (kilometers) distant. A limestone bridge 300 m long and 10 m high carried a canal 15 m wide over a stream and valley to supply both domestic and irrigation water. More than two million heavy blocks of limestone were used in the bridge.

2.2. Rome

The aqueducts of Rome are especially remarkable. For over 400 years after the founding of Rome, water from the Tiber River supplied the city. The first aqueduct was built in 312 B.C. Two were begun in Caligula's reign and finished in Claudius' reign. By the time Frontinus became water commissioner of Rome in 97 A.D., there were eight main aqueducts bringing waters of high quality from springs and rivers to the fastidious Romans. Another aqueduct from a lake brought unpalatable water. These aqueducts were partly below ground (with some tunneling), partly on substructures, and partly on arches. Lead pipes delivered water to the public and to the wealthy. The Romans even constructed some inverted siphons (a pressure pipe dipping into a swale or valley and discharging at nearly the same elevation as the entrance) made of lead pipe several cm (centimeters) thick. Greeks, however, probably invented the siphon. A large Greek siphon was constructed at Pergamon about 180 B.C.

The Romans used a practical method for determining whether a potential water source was safe. If the nearby inhabitants who used the water stayed healthy, the Romans appropriated it.

Romans also built aqueducts in many other places. One of the most spectacular leaps the Gard River near Nimes, France in three graceful tiers of carefully fitted cut stone arches without joint mortar. The total length of the arched structure is nearly 275 m and the entire aqueduct was 48 km long. Another, built in 100 to 110 A.D., consists of two tiers of arches with a maximum height of 36 m and a length of 823 m. It still supplies water to Segovia, Spain.

Many ancient cities relied on water supplied by rainwater from roofs and stored in cisterns. Fortresses like Megiddo, Israel, are one example. Constantinople with huge cisterns under the city is another.

2.3. London

The oldest water supply system (with a well-known history of progress) in Europe is that for London. The remains of three giant water-lifting systems dated in the first century were found near the heart of Londinium, the Roman name for London. They could have raised 140 cubic meters per day by using a chain to pull buckets up from a deep well. Romans imported a culture of bathhouses and high standards for clean water, and probably local waters, including the Thames, were so polluted that the water-lifting systems were an important source of fresh water.

Work commenced in 1235 on a water system about 5.5 km long from a lead-lined cistern to London was finished 50 years later. A 150 mm lead pipe system from Tybourne (a brook) was begun in 1236. Other sources from brooks and springs were introduced from time to time. There were, however, no pipes to individual houses. House supply was water in buckets carried by porters, until in 1582 water was conveyed in lead pipes from a "forcier" at London Bridge. The "forcier" consisted of a water wheel about six meters in diameter supplying power to 16 pumps made of pistons 175 mm diameter in cylinders nearly 1.5 m long. The whole machine was mounted between piers of the bridge on a wooden frame that rose and fell with the tide. At low tide, the water flowing past the water wheel was swift, and the pumps could force a stream of water over a church steeple. Eventually, there were three such machines operated by the family of the builder until 1701.

Over the objections and interferences of the land owners, a canal called the New River 5.5 m wide was begun in 1609 from Chadwell Spring to London, a straight line distance of about 30 km but a winding route of 60 km. King James I furnished some funds for completion in return for half the profits. (Later, the king's horse threw him into the New River and he nearly drowned.) The water level of the full reservoir at the end of New River was 25 m above high water in the Thames, so water could be delivered to cisterns in lower stories by gravity. As demand for water in upper stories increased, a 45-kilowatt steam engine was purchased in 1787 to provide a high-pressure supply. Wooden pipe mains were used until 1810, when wood began to be replaced with iron that could withstand 90 m of water pressure—a great convenience.

Water from the Thames was so turbid that a filter plant was installed in 1829. It consisted of ponds to allow coarse sediment to settle followed by a filter consisting of rows of parallel channels covered with bricks, then gravel, then coarse sand to form a bed for fine sand. Each of the three layers was 0.6 m thick, so the water had to pass downward through 3.6 m of sand and gravel to reach the drainage channels. When the sediment on the fine sand became too dense to allow satisfactory percolation, the top was scraped off and fresh sand added. The filter was so successful that laws were passed in 1855 compelling filtration of all river water used in London. Another fifteen years were to pass before the beneficial action of bacteria and other microorganisms in the filter beds would be understood.

A major contribution to the conservation of water was the flush toilet perfected by Thomas Crapper by 1884. From Minoan times until about 1880, wastes were flushed away by lifting a plug in the water supply. In London, the plugs leaked and some users were too lazy to reinsert the plug. The useless waste of water appalled the Board of Trade which sought means to conserve it. With Crapper's Valveless Water Waste Preventer, leakage was prevented by breaking the siphon action in the storage tank.

3. Tunneling

For our purpose herein, tunneling is the drilling or excavation of a nearly horizontal aqueduct through a hill or mountain to avoid a route over or around the obstruction. Tunneling used to be an inordinately slow process. Although Chinese made black powder by 80 A.D., it was for many centuries unknown to Mediterranean people who either chiseled their way through rock or heated the face of the tunnel and flaked the rock with cold water. Tunnels were dug from both sides of a mountain, sometimes scarcely meeting. At one project, the tunnels passed each other in four years of digging. (The hydraulic engineer, who had been absent during this time, solved the problem by a survey for a short connecting tunnel. One of the best-known tunnel aqueducts was built under King Hezekiah about 700 B.C. to bring water to Jerusalem through solid rock. The tunnel was two m high by 530 m long.

Tunneling in rock became easier and faster with the advent of black powder first used in Europe for the Midi canal in France in the 17th century. Nobel's discovery of dynamite in 1866 revolutionized rock excavation. Tunnel progress in hard rock increased from less than a meter per week in the 17th century, to 30 m at the end of the 19th century, and to 250 m per week with full-face boring machines. Tunneling has become so effective that many large cities with no surface space for storm water storage are building tunnels 30 m below ground level for storing the peaks of storm water runoff.

-
-
-

Bibliography

Angelakis, A.N., Koutsoyiannis, D., and Tchobanoglous, G. (2004). Urban wastewater and stormwater technologies. Internaational Water Association, (in press). [This paper presents a valuable and extensive survey of Minoan and ancient Greek technology in domestic waste and storm water disposal]

Babcock, R.H., Bowers, A.E., Dart, F.J., Fulton, J.P., Fulton, H.O., Knowlton, K.F., Maier, F.J., McKinney. R.E., Middleton, F.M., Silvey, Taras M.J., White, G.C., and Wolman, A. The quest for pure water Vol. II. (1948). American Water Works Association. [This book includes all the standard methods used in treating water to culinary standards. Each section is written by an expert in the subject]

Biswas, A.K., Dakang, Z., Nickum, J.E., and Chanming, L. (1983). Long-Distance Water Transfer.Dun Laoghaire, Ireland.Tycooly International Publishing Ltd. [This presents problems in water transfer and systems in Egypt, Japan, Texas, but mainly in China]

Draffin, J.D. (1939). The story of man's quest for water. Champaign, Illinois.The Garrard Press. [This book presents and unusually complete, concise history of water supply from ancient times to 1935 A.D.]

Encyclopaedia Britannica. (1981). Chicago/London/Toronto/Geneva/Sydney/Tokyo/Manila/Seoul. Encyclopaedia Britannica, Inc. [This compendium of 33 volumes presents concise descriptions of a great many subjects]

Linsley, R.K., Franzini, J.B., Freyberg, D.L., and Tchobanoglous, G. (1992). Water-Resources Engineering, 4th Ed. New York, McGraw-Hill, Inc. [This textbook is a classic, comprehensive and concise treatise on virtually all aspects of public and irrigation water supply and the treatment of water and wastewater]

Metcalf & Eddy. Revised by Tchobanoglous, G., Burton, F.L., and Stensel, H.D. (2003). Wastewater Engineering. Treatment and Reuse, 4th Ed. New York. McGraw-Hill. [This book is an extensive treatise on constituents in wastewater, treatment processes and selection, physical and chemical unit operations, aerobic and anaerobic biological processes, disinfection processes, and reuse of liquid and solid wastes]

Turneaure, F.E. and Russell H.L. (1908) Public Water-Supplies, 2cd.Ed. New York, John Wiley & Sons. [This book gives a thorough and delightful glimpse into engineering practice at the beginning of the 20th century]

Biographical Sketch

Robert L. Sanks, Consulting Engineer

Education:BS/1940/Civil Engineering

MS/1949/Structural Engineering

PhD/1965/Sanitary Engineering.

Registration:1966. Professional Engineer, Montana 2704PE. Previously registered in California, Utah.

Relevant Experience and Qualifications:

Environmental

For Christian, Spring, and Sielbach Associates: responsible for preliminary design, cost estimating, and facility plan reports for sewage treatment at Town of Livingston (secondary treatment), Crow Agency (physical-chemical), Rocky Boy (spray irrigation, land disposal), Deer Lodge (aerated lagoon), Browning (aerated lagoon). Startup, operation, and operator training at Colstrip and Poplar, operation of a biodisc pilot plant at Livingston. Design and operation of a direct filtration pilot plant and preliminary design of water treatment plant at Colstrip. 1970-1981.

Innovations

Invention of ramp in trench-type wet wells to make cleaning easy and quick. Introduced trench-type wet wells to Hydraulic Institute and to the profession. Research to improve performance in normal operations. 1990-present.

Responsible for the first use of these technologies in Montana: (1) Land disposal of sewage (by spray irrigation at Rocky Boy), (2) direct filtration (of Yellowstone river water for Colstrip), (3) secondary sewage treatment by biodisc (at Livingston), (4) use of onsite pilot plant tests for design of sewage treatment (at Livingston), (5) use of onsite pilot plant tests for design of water treatment facilities (at Colstrip)—all successful projects. (For several years, the Livingston plant produced the most highly treated wastewater in Montana.) 1970-1981

Pumping stations

Director of pumping station design conference 1979-1982, Editor of Conference Proceedings 1982 (1575 pp), Editor-in-chief and author or co-author of seven chapters in *Pumping Station Design*, Editor-in-chief and author or co-author of ten chapters in *Pumping Station Design* 2cd Ed, director and lecturer at numerous workshops on the subject 1989-1997, manager and principal investigator of self-cleaning wet wells for constant speed submersible pumps 1991-1995 (published by U.S. EPA in 1995 as "Improvements in pump intake basin design"). 1994 – present.

PUBLICATIONS

Five books: *Pumping Station Design* 2cd Ed (1012 pp) Butterworth-Heinemann 1998, *Pumping Station Design* (858 pp) Butterworth Publishers 1989, *Water Treatment Plant Design for the Practicing Engineer* (845 pp) Ann Arbor Science Publishers 1976, *Land Treatment and Disposal of Municipal and Industrial Wastewaters*, (310 pp) Ann Arbor Science Publishers 1976, *Statically Indeterminate Structural Analysis* (602 pp) Ronald Press 1961. Seven monographs, four proceedings, numerous papers.

HONORS AND AWARDS

Pumping Station Design by Sanks *et al* received the only award "Excellence" given by the Professional & Scholarly Division of the American Association of Publishers for any engineering book published in 1989. Society of the Sigma Xi, Chi Epsilon, Fuller Award (American Water Works Association), Fellow—National Science Foundation 1961-3, Wall of Fame—Fullerton Union High School 1987, Who's Who in America 1988-present.