WATER SCIENCE AND TECHNOLOGY: HISTORY AND FUTURE

James Dooge
Centre for Water Resources Research, University College, Dublin, Ireland

Keywords: water science, water supply, drainage, inland navigation, waterpower, renaissance, hydraulic engineering, hydraulics, hydrology, wastewater engineering, turbines, sociology

Contents

1. Introduction

1.1 The Properties of Water

Water is all-pervasive in nature and in the life of humanity. Water has played a unique role in the evolution of life, the development of human society, and in the intellectual and spiritual dimensions of the human concept of nature. This widespread influence has been throughout history an important influence on the development of both water science and water technology in all parts of the world.

Water which presents itself to our senses as a simple substance has many unexpected and anomalous properties. Water exists on our planet Earth in great abundance in liquid form because water is liquid at the average global temperature of around 15°C. In contrast, water on the two adjacent planets occurs only as water vapor on Venus and only as ice on Mars. It has been estimated that if the Earth were 5 percent closer to the sun our hydrosphere (i.e. the water envelope surrounding the Earth) would be in vapor form and that if the Earth were 5 percent further from the sun our hydrosphere would consist of solid ice.

The fact that water is liquid at 15°C is itself anomalous. Oxygen (O) is an immediate neighbor of sulfur (S) in the chemical table of elements. In spite of this, there is a wide gulf between the properties of water (H_2O) which is an odorless liquid and hydrogen sulfide (H_2S) which is a pungent gas. Physical chemistry can explain the difference as being due to hydrogen bonding in the case of water. This should prepare us for other surprises in dealing with the properties of water, in spite of its simple appearance. For example, the surface tension of water is two or three times that of other common liquids. In consequence, a greater amount of water will be retained around the contact points of the particles in an unsaturated porous medium. This makes water a more efficient agent for retaining water in an unsaturated soil, thus prolonging the life of the surface vegetation during drought periods.

Water has the highest latent heat of vaporization and the highest specific heat of any substance and thus maximizes the amount of energy that can be redistributed through evaporation in the tropics, transportation as vapor by atmospheric circulation, and its reprecipitation as rain in middle latitudes. This tends to reduce the variation in temperature that would otherwise exist between these two regions and so increase the amount of land available for productive agriculture under comfortable living conditions. Water is unique in being an almost universal solvent and thus provides the major pathways both for the nutrients necessary for health and for the toxic substances that are inimical to health. The provision of the former and the control of the latter have been a concern of water technology throughout the ages.

One difficulty for an overview of the topic is that of scale. The range of scales involved in the study of water is enormous. In space they vary from the molecular scale of 10^{-10} meters up to the grid scale of a global circulation model of 10^{5} meters i.e. a span of 15 orders of magnitude. In time they vary from 10^{-13} seconds which is the interval at which water molecules form and reform clusters up to 3×10^{6} seconds which is the scale of the inter-annual variation of climate, thus giving a range of time scale of over 19 orders of magnitude. This immense range of scales can be roughly divided for the purpose of analysis into four parts: (a) the lowest range from 10^{-10} meters to 10^{-6} meters involving water molecules and molecular clusters which is the domain of water chemistry; (b) a higher range from the continuum point of a fluid (10^{-5} meters) to the average mixing length of turbulent flow (10^{-2} meters) which is the domain of fluid mechanics and hydraulics; (c) a further range from the 10 meter scale of an experimental land surface plot to the 10^{4} meter scale of a typical drainage catchment which is the domain of classical hydrology; and (d) the largest scale of 10^{6} meters and upwards which is the domain of regional and global hydrology.

1.2 Scope of Water Science and Technology

Water science is a subject vast in scope and variegated in relation to its interests and techniques. The situation is further complicated by the fact that the flow of water in the hydrological cycle interacts with other geophysical cycles such as the cycle of erosion and deposition of sediment and the biogeochemical cycles of such important elements as carbon (C), nitrogen (N) and sulfur (S). The geophysical cycles (water, sediment, and the key chemical elements) not only interact with each other but this total geosystem interacts with the global and the local economic and social systems. Changes in the geosystem influence both economic development and population growth and in turn the geosystem is affected by changes in these two factors. Water technology has been concerned throughout history with the harnessing of water resources for economic livelihood and with the effects of economic development on water quality. Not only is water essential for life itself but a plentiful supply of clean water is essential for health. The single major cause of death throughout history has been the contamination of water supplies.

In the chapter on Freshwater Resources in the 1992 Report on the Agenda of Science for Environment and Development into the 21st Century (ASCEND 21), Ayibotele and Falkenmark characterize the relation of water to the environment as follows:

(1) Water is a unifying agent of the natural ecosystems with functions similar to the blood and lymph of the human body.
(2) Water is consumed in biomass production which is therefore limited by local water availability.
(3) Water circulation is an important element of the global cycles and in this sense is intimately linked to the climate.
(4) Water is a fundamental resource on which depend life support systems and which has to be equitably shared between all those living in a particular river basin.
(5) Water is a crucial link in the causality chain producing biodiversity disturbances.

The above list is not exhaustive and can be extended to include other key topics such as water-related disasters (floods, droughts, sudden glacier outflows, mud flows), which account for a substantial proportion of deaths due to natural disasters and an overwhelming proportion (about 90 percent) of persons affected by natural disasters. Experts may differ about the contents of such a list or about the relative importance of the various items but the overall message is clear. Water science and water technology has always been of prime importance to society and will be of increasing importance for the future.

1.3 Selection of Topics

The treatment of a topic as complex as water science and technology within the limits of a single article must of necessity be selective in relation to a number of aspects of the problem and must also avoid undue detail in the treatment of the selected topics. In regard to the many scales of interest in water science discussed in section 1.1 above, the emphasis here will be centered around the human scale appropriate to water use by a local community. To be efficient in water use at this scale, one must take account of the scientific principles applicable to the actual phenomena arising at smaller scales than the human and equally one must take into account the impacts of larger scale phenomena on conditions at the scale of primary interest.

It is also necessary to determine the coverage of geographical regions and historical periods. In doing this it is necessary to explore the treatment of the subject in archaeology, in history, in literature as well as in science and technology. Because of the background of the author and because of the availability of the basic information, an emphasis on the European region is almost unavoidable. A reader interested in a specific topic or region would be well advised to redress any bias involved by supplementary reading of the appropriate key references provided in the bibliography at the end of the article and in the more specialized publications referenced in turn by them.

In regard to the coverage of the span of human history, some selectivity is also necessary. Four periods of special interest have been chosen as being of particular importance from a number of viewpoints. These are: 1) the ancient world; 2) the medieval world; 3) the high Renaissance; 4) the nineteenth century; and 5) the twentieth century. These latter advances in individual areas of water science and technology have been well covered in the end of century review papers in a large number of specialized journals. The nature and effect of the outstanding advances are dealt with in the other articles in this Part of the Volume. The five historical sections are supplemented a section on the future describing the nature of present problems and future trends and discussing appropriate policies for the future integrated management of water resources. The latter views are clearly the personal views of the author.

2. The Ancient World

2.1 Water Supply and Drainage

The earliest food gatherers camped near springs or beside rivers and the earliest farmers tended to group in the neighborhood of springs. In prehistoric Europe and the Near East these springs, which were natural or hand-dug, and rarely more than 5 meters deep, were usually encased in some fashion. As communities increased in size, deeper wells up to 30 meters deep and 2 meters in diameter were dug by hand and lined with stone. Cisterns were also dug to store water underground and these evolved from primitive timber-lined shafts to large masonry structures pillared and reached by a flight of stairs. Piping systems used to distribute water from cisterns have been found in the ruins of palaces dating from 2700 BC.

The classical example of seasonal irrigation was in Egypt where there was a gradual development from uncontrolled irrigation to controlled basin irrigation. Another classical example of irrigation and land drainage in historic times was that of Mesopotamia, i.e. the land between two rivers (Tigris and Euphrates). The riverbeds were above the level of the intervening plain and the flood flows occurred in the wrong season for agriculture thus requiring a system of storage and controlled distribution.

The first large-scale transfer of water by subsurface conduits from aquifers and alluvial fans in mountainous areas to distant settlements in dry areas seems to have arisen around 1000 BC in Armenia. Such *qanats* became widespread on the Persian Plateau and some are still in operation in present day Iran. A qanat is an underground sloping tunnel, ventilated and accessed by a number of vertical shafts, which carries water over long distances without serious losses due to surface evaporation. The technology is also found in North Africa, Spain, and South America, as well as in Afghanistan and Chinese Turkestan. Scholars are divided as to whether this is due to diffusion of the technique from Persia or to individual development, with a majority of authorities favoring the former explanation. At some points the conduit was carried across ravines on corbelled arches, one such example in Northern Iraq dates back to 700 BC

In classical Greece, the commonest form of long distance conduit was the terracotta pipeline, (usually 20–25 centimeters in diameter) sometimes supported by stones over low points or laid along the bottom of a large access channel or tunnel. To avoid a long winding trajectory or expensive tunneling, the Greeks introduced the use of siphons (previously used at a small-scale for mixing wines and other liquids) into the construction and operation of water conduits.

The evolution of the Roman aqueducts began about 300 BC under the pressure of population increase. For over 400 years before that time, the source of water supply for Rome had been the river Tiber supplemented by individual wells or cisterns. The large aqueducts were designed essentially for municipal use and for communal purposes such as the bath houses which were essentially centers of social activity. The first aqueducts were underground with the same cross section as a typical Persian qanat, or Etruscan cuniculum, i.e. 0.6 m wide and 1.2 m high at a slope of 1: 2000. The main feature of the later Roman aqueducts was their scale and in particular the large quantities of water transported on a flow-through basis without any appreciable storage. The later aqueducts were brought through at a higher level to provide a good head in the water tower (*castellum*) for distribution of the water within the city. The public water supply of Rome in 100 AD has been estimated as being over a thousand liters per head per day.

Some thought was given by the Roman engineers to the question of water quality and wastes. The local inhabitants and animals in the source area were studied for signs of disease. Water was boiled and the vessel examined for evidence of residues. Stilling basins were provided at the head of the aqueduct. In some cases, the choice of clear sparkling spring water on the basis of its appearance led to subsequent problems of encrustation of the conduits. Methods of purifying water on a domestic scale for drinking purposes included boiling, filtration through wool or wick siphons, and the reduction of lime content by the addition of salt or of a small quantity of Algerian wine.

The arrangements for handling wastewater were largely undeveloped compared with the elaborate arrangement for water supply. In the ruins of Pompeii, the domestic toilets were found to be located for convenience next to the kitchen. In most cases the waste was accumulated in a cesspit located either below the toilet or in the backyard of the dwelling. Public toilets in the baths or elsewhere, open rooms which lacked any degree of privacy, were better serviced. The large quantities of water from the public baths were carried in a continual flow along sewers located directly under these public toilets. The ultimate disposal of these wastes was not so satisfactory. It must also be remembered that cities like Rome and Pompeii did not reflect conditions in most Roman towns where disposal of wastes was even less satisfactory. Information about sanitary provisions for the poor is not well represented in the literature of any age. It is salutary to recall that the average life span in Classical Greece and Rome was about 25 years.

2.2 Mechanisms and Structures

A number of techniques were developed in the ancient world to improve the efficiency of the abstraction of water from wells or from irrigation ditches. Some of these evolved ultimately into the differing forms of modern pumps. The most primitive device was some form of scoop used by one person to take water from a shallow well or by two persons to haul with ropes from a deep well. A development of these primitive methods was the *shadoof*, still used in a number of countries four thousand years later, which raises a bucket from a well by means of a lever and counter-weight. This primitive mechanism led eventually to the modern suction pump. Another line of evolution was the introduction of a pulley hoist followed by the use of a chain of pots which led in turn to a wheel of pots (or Persian wheel) in which the rotation of the wheel by man or beast was used to raise water, a primitive ancestor of the centrifugal pump. A third independent development was that of the screw pump about 400 BC and its application to pumping water by the device known as the Archimedean screw, still used today and the forerunner of the modern mechanical screw pump.

The reverse process of converting an available difference in water level into rotary motion in about 100 BC represents an important stage in the development of technology i.e. the replacement of muscle power by a primitive machine. The main use of these primitive mills was to relieve the burden of grinding corn by hand. This is well expressed by the poet Antipater in the first century BC (see Forbes, 1965: vol. 2, p. 88; Gimpel, 1977: 7).

Cease from grinding,
ye women who toil at the mill;
even if the crowing cock announce the dawn.
For Demeter has ordered the nymphs
to perform the work of your hands
and they leaping down on top of the wheel
turn its axle, which with its revolving spokes
turns the heavy concrete Phrygian millstones.

This primitive mill with a horizontal wheel and a vertical axle was directly coupled to the horizontal millstone. The low efficiency of this primitive mill was greatly surpassed by the Roman mill, which was a vertical wheel on a horizontal axle connected through gearing to the vertical shaft of the horizontal millstones. The undershot version of this type of vertical water wheel was easier to construct and operate than the more efficient overshot type. It is probably for this reason that the undershot vertical wheel remained in use for several centuries.

The construction of dykes and dams for various purposes of water control was quite common in classical times. The oldest known dam is the 11 m high Sadd el-Kafara dam 20 miles south of Cairo, which is over 4500 years old. The apparent purpose was to create a reservoir (capacity 0.6 million cubic meters) to facilitate the operation of nearby alabaster quarries. There are also written records, though no physical remains, of dams in Mesopotamia dating back 4000 years. In 703 BC and 690 BC, Sennacherib initiated the construction of the two dams that supplied Nineveh and its gardens with ample water. In Arabia, a dam was built at Marib in 750 BC and raised in 500 BC by the Sabaens (i.e. the people of Sheba or modern Yemen). It lasted for well over a thousand years before being destroyed by an extreme flood around 575 AD. A system of a large number of small dams (more than 17 000 in 130 square kilometers) was used by Nabateans about 300 BC to create a viable method of agriculture in the Negev desert. The Romans built dams throughout the empire, notably in Spain. The only three Roman dams that survive in Italy are near Subiaco and were constructed by Nero around 50 AD to create artificial lakes near his villa.

2.3 The Origins of Water Science

In the ancient world, water technology developed as a result of trial and error and a limited diffusion of practical ideas. Systematic thinking in relation to water was much slower to emerge. The early cosmologies pictured the Earth as floating on water as exemplified by the pictorial representation by Rabbi Louis Jacob of the cosmology of Genesis (*c*. 1000 BC) involving the Earth, the foundations of the deep and the pillars of the sky or by the Chinese cosmology of about 300 BC representing the Earth as an inverted hemispherical bowl floating on water within a hemispherical cover. Thales (624–546 BC) of Miletos, recognized by Aristotle as the first philosopher, adopted the concept of a floating Earth and postulated that water is the original substance and the material cause from which everything else originates. Such a view could naturally arise from the existence of water in all three phases (water vapor, liquid water, ice) and the effect of rainfall in a semi-arid climate.

Over the next 200 years a number of philosophers discussed the major elements of the hydrological cycle and developed the concepts and the relationships of evaporation, precipitation and streamflow. Anaximander (610–545 BC) of Miletos discussed the evaporation of the ocean by the sun. He believed that the ocean originally covered all the Earth and that the emergence of dry land was a process which would continue in the future. Shortly afterwards, Xenophanes (570–475 BC) connected evaporation from the ocean with clouds and winds and suggested that rain from clouds was the origin of springs and streams. He also suggested that the saltiness of the ocean arose from substances carried by streams which were not removed from the ocean during evaporation. This represents the emergence of the atmospheric interpretation of the concept of the hydrological cycle. The first experimental proof of evaporation is due to Hippocrates of Cos (460–380 BC?) who weighed a vessel containing water over a period of time.

The general view in the ancient world was that precipitation was not sufficient to provide the observed amount of flow in springs and streams and that water was conveyed by some mechanism through underground caverns from the sea to the elevated ground. Both Plato (427–347 BC) and Aristotle (385–322 BC) discussed the question of the hydrological cycle. The discussion by Plato in his Phaedo and his Critias differ somewhat. The former is based on the concept of Tartarus a huge subterranean reservoir which fed both the springs and the oceans. The latter suggests a role for the retention of rainfall in the soil. Aristotle rejected the concept of a vast subterranean storage reservoir suggested by Anaxagora (500–428 BC) and by Plato and put forward an alternative explanation based on the transformation of air or vapor into water in a sponge-like interior of the Earth.

Quantitative measurements of hydrological elements in ancient times seem to have been largely motivated by political concerns relating to taxation. Nilometers which date from about 3000 BC measured the level of the Nile in order to forecast the probable size of the harvest and therefore of the central revenue available from taxation. The earliest measurements of rainfall of which we have a record date from India in the fourth century BC and were used for fixing the level of taxation of the harvest on the basis of the variation in the monsoon rainfall.

Authorities differ in regard to the degree of knowledge of hydraulics available to the designers of the great aqueducts of Persia, Greece, and Rome. Analysis of Frontinus' discussion of changes in discharge due to leakage and illegal abstractions from the Roman aqueducts reveals that he based his analysis of changes of flow on a comparison of cross-section only. It seems that either the relatively small variations in slope and roughness in a given aqueduct kept the resulting error within bounds or that only sections of standard slope were used for comparison.

Hero of Alexandria, who was probably a contemporary of Frontinus (40–103 AD), had a clear understanding of the hydraulics of stream flow when he wrote:

It is to be noted that in order to know how much water the spring supplies it does not suffice to find the area of the cross section of the flow which in this case we say is 12 square digits. It is necessary also to find the speed of flow, for the swifter is the flow, the more water the spring supplies, and the slower it is, the less. (Rouse and Ince, 1957: 22)

Hero goes on to describe the most convenient way of measuring the flow of the spring:

One should therefore dig a reservoir under the stream and note with help of a sundial how much water flows into the reservoir in a given time, and thus calculate how much will flow in a day.

This clear recognition of the importance of the time element and its measurement had no impact in the ancient world and the concept of continuity of discharge was not returned to for another 1500 years.

-
-
-

Bibliography

Biswas A. K. (1970). *History of Hydrology*, 336 pp. Amsterdam and London: North-Holland. [Standard work on the subject covering the period from 3000 BC to 1900 AD.]

Forbes R. J. (1964–1965). *Studies in Ancient Technology*. Leiden: Brill. [See especially, Volume I, pp. 149–194 on Water Supply; Volume II, pp. 1–79) on Irrigation and Drainage and pp. 80–130) on Power. Authoritative review of developments from the earliest times to 1500 AD.]

Garbrecht G., ed. (1987). *Hydraulics and Hydraulic Research: A Historical Review*, 362 pp. Rotterdam: Balkema. [A series of presentations by individual experts on diverse aspects of the history of hydraulics, hydraulic engineering and water resources development since 5000 BC.]

Gies F. and Gies J. (1994). *Cathedral, Forge and Water Wheel*. 358 pp. New York: Harper Collins. [A wide-ranging treatment of technology and invention in the Middle Ages.]

Gimpel J. (1977). *The Medieval Machine*, 274 pp London: Gollancz. [A revisionist treatment of what he terms the industrial revolution of the Middle Ages.]

Levi E. (1995). *The Science of Water: The Foundation of Modern Hydraulics*, 649 pp. Trans. D.E. Medina from the Spanish *El Agua Segun La Cienca*. New York: American Society of Civil Engineers. [A lively discussion on the development of hydraulic concepts, theorems and formulae describing false starts as well as successes.]

National Research Council (1991). *Opportunities in the Hydrological Sciences*. 348 pp. Washington, D.C.: National Academy Press. [Excellent account of the present state of scientific hydrology.]

Needham J. (1965, 1971). *Science and Civilisation in China*. Cambridge: Cambridge University Press. [See Volume 4, pp 330–362 on Water-raising machinery; Volume 4, pp. 362–408 on Water flow and descent; Volume 4, pp. 211–378 on Hydraulic engineering.]

Parsons W. B. (1939, 1968). *Engineers and Engineering in the Renaissance*, 661 pp. Cambridge, MA: MIT Press. [Excellent coverage of the topic including 10 chapters on hydraulic engineering.]

Robins J. (1946). *The Story of Water Supply*, 207 pp. London: Oxford University Press. [A good description of developments from earliest time in a number of cultures.]

Rouse H. and Ince S. (1957). *History of Hydraulics*, 269 pp. Iowa City: Iowa Institute of Hydraulic Research. [Standard publication on the subject covering the period from the earliest times until 1950 AD]

Schmidheiny S. (1992). *Changing Course. A Global Business Perspective on Development and the Environment*, 374 pp. Cambridge, MA: MIT Press. [An authoritative treatment of the topic of the reconciliation of environmental concerns with business efficiency by 50 business leaders prepared by the Business Council for Sustainable Development as an input to the 1992 Rio Conference on Environment and Development.]

Singer C., Holmyard E. J., Hall A. R., and Williams T. J. (1956, 1958). *A History of Technology*. Oxford: Clarendon Press [See Volume I, pp. 520–552; Volume 2, pp. 663–694; Volume 4, pp. 199– 213, pp. 489–519, and pp. 548–573; Volume 5, pp. 522–551 and pp. 552–568.]

Sprague de Camp L. (1993). *The Ancient Engineers*, 408 pp. New York: Barnes and Noble. [Covers both ancient and medieval times by region.]

Young G. I., Dooge J. C. I. and Rodda J. (1994). *Global Water Resource Issues*, 194pp. Cambridge: Cambridge University Press. [Based on the detailed background papers and the Report of the Dublin 1992 Conference on Water and the Environment.]

Zebidi H. (1998). *Water: A Looming Crisis*, 536 pp. Technical Documents in Hydrology 18. Paris: UNESCO. [Proceedings of the International Conference on World Water Resources at the Beginning of the 21st Century. UNESCO, Paris, June 1998.]

Biographical Sketch

Professor James C. I. Dooge graduated from the National University of Ireland B.E. (Civil Engineering), B.Sc. (1942). M.E. (NUI 1952). M.Sc. in Fluid Mechanics and Hydraulics (Iowa) 1956). Junior Engineer on river improvement works 1943–1946. Design Engineer on hydroelectric projects 1946–1958. Professor of Civil Engineering, University College Cork 1958–1970. Professor of Civil Engineering, University College Dublin 1970–1984. Visiting Professor in Engineering Hydrology, University College Galway 1984–1986. Research Consultant, Centre for Water Resources Research, University College Dublin, 1986–to date. President of the Institution of Engineers of Ireland 1968–1969. President International Association for Hydrological Sciences 1975–1979. President of the Royal Irish Academy 1987–1990. President of the International Council for Science 1993-1996. Honorary Doctorates from the Universities of Wageningen (Dr. Agr. Sc. 1978), Lund (Dr.Tech. 1980), Birmingham (D.Sc. 1985), Dublin (Sc.D. 1988), Heriot-Watt (Dr. Eng. 2000), Cracow (Dr. Ing. 2000), NUI (D.Sc. 2001), Madrid (D. Sc. 2001). Foreign Member of the Polish Academy of Sciences. Foreign Member of the Russian Academy of Sciences. Foreign Member of the Spanish Academy of Sciences. Foreign Member of the Royal Academy of Engineering (UK). International Prize for Hydrology (1983). Bowie Medal of the American Geophysics Union 1986. Leonardo da Vinci Medal of the European Society for Engineering Education 1990. John Dalton Medal of the European Geophysical Society 1998. International Prize for Meteorology 1999.