HYDROLOGIC AND HYDRAULIC SCIENCE AND TECHNOLOGY IN ANCIENT GREEK TIMES

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1. INTRODUCTION

The approach typically followed in problem solving today is represented by the sequence Understanding – Data – Application, in this order. However, the historical evolution in the development of water science and technology (and other scientific and technological fields) followed the reverse order: application preceded understanding (1). Thus, technological application in water resources has started in Greece as early as in *ca.* 2000 BC. Specifically, in the Minoan civilization (see the entry on Urban Water Engineering and Management in Ancient Greek Times) and later in the Mycenaean civilization several remarkably advanced technologies have been applied for groundwater exploitation, water transportation, water supply, stormwater and wastewater sewerage systems, flood protection, drainage, and irrigation of agricultural lands. Much later, around 600 BC, Greek philosophers developed the first in history scientific views of natural phenomena. In these, hydrological and meteorological had a major role, given that water was considered by the Ionic school of philosophy (founded by Thales of Miletus; *ca.*624-545 BC) as the primary substance from which all things were derived. Even later, during the Hellenistic period, significant developments were done in hydraulics, which along with progress in mathematics allowed the invention of advanced instruments and devices, like the Archimedes's water screw pump.

2. SCIENTIFIC VIEWS OF HYDROLOGIC PHENOMENA AND HYDRAULICS

It has been believed by many contemporary water scientists that ancient Greeks had not achieved understanding of the water related phenomena, and had a wrong conception of the hydrological cycle. This belief is mainly based on Plato (*ca.* 429-347 BC), who is his dialogue Phaedo (14.112) expresses an erroneous theory (based on Homer's poetical view) of hydrological cycle; notably, his wrong theory was adopted by many thinkers and scientists from Seneca (*ca.* 4 BC-65 AD), to Descartes (1596-1650).

However, long before Plato, as well as much later, several Greek philosophers had developed correct explanations of hydrological cycle, which reveal good understanding of the related phenomena. In fact, as Koutsoyiannis and Xanthopoulos (2) note, the first civilization in which these phenomena were approached in an organized theoretical manner, through reasoning combined with observation, and without involving divine and other hyperphysical interventions, was the Greek civilization. The same authors catalog a number of ancient Greek contributions revealing correct understanding of water related phenomena. Thus, the Ionic philosopher Anaximenes (585-525 BC) studied the meteorological phenomena and presented reasonable explanations for the formation of clouds, hail and snow, and the cause of winds and rainbow. The Pythagorean philosopher Hippon (5^{th} century BC) recognizes that all waters originate from the sea. Anaxagoras, who lived in Athens (500-428 BC) and together with Empedocles (*ca.* 493-433 BC) is recognized as the father of experimental research, clarified the concept of hydrological cycle: the sun raises water from the sea into the atmosphere, from where it falls as rain; then it is collected underground and feeds the flow of rivers. He also studied several meteorological phenomena, generally supporting and completing Anaximenes's theories; his theory about thunders, which fought the belief that they are thrown by Zeus, probably cost him imprisonment (*ca.* 430 BC). In particular, he correctly assumed that winds are caused from differences in the air density: the air, heated by the sun, moves towards the north pole and leaves gaps that cause air currents. He also studied Nile's floods attributing them to the snowmelt in Ethiopia. The "enigma" of Nile's floods (which, contrary to the regime of Mediterranean rivers, occur in summer) was also thoroughly studied by Herodotus (480-430 BC), who seems to have clear knowledge of hydrological cycle and its mechanisms.

Aristotle (384-323 BC) in his treatise Mereorologica clearly states the principles of hydrological cycle, clarifying that water evaporates by the action of sun and forms vapor, whose condensation forms clouds; also, he recognizes indirectly the principle of mass conservation through hydrological cycle. Theophrastus (372-287 BC) adopts and completes the theories of Anaximenes and Aristotle for the forming of precipitation from vapor condensation and freezing; his contribution to the understanding of the relation between wind and evaporation was significant. Epicurus (341-270 BC) contributed to physical explanations of meteorological phenomena, contravening the superstitions of his era.

Archimedes (287-212 BC), the famous Syracusan scientist and engineer considered by many as the greatest mathematician of antiquity or even of the entire history, was also the founder hydrostatics. He introduced the principle, named after him, that a body immersed in a fluid is subject to an upward force (buoyancy) equal in magnitude to the weight of fluid it displaces. Hero (Heron) of Alexandria, who lived after 150 BC, in his treatise 'Pneumatica' studied the air pressure, in connection to water pressure, recognizing that air is not void but a substance with mass consisting of small particles. Also, he is recognized (3) as the first who formulated the discharge concept in a water flow and made flow measurements.

Unfortunately, many of these correct explanations and theories were ignored or forgotten for many centuries, only to be re-invented during Renaissance or later. This was not restricted to water related phenomena. For example, the heliocentric model of the solar system was first formulated by the astronomer Aristarchus of Samos (310-230 BC) 1800 years before Copernicus (who admits this in a note). Aristarchus also figured out how to measure the distances to and sizes of the Sun and the Moon. In addition, not only did ancient Greeks know that Earth is spherical, but also Eratosthenes (276-194 BC) calculated, 1700 years before Columbus, the circumference of the earth, with an error of only 3%, by measuring the angle of the sun's rays at different places at the same time; in addition t he geographer Strabo (67 B.C.-23 AD) had defined the five zones or belts of Earth's surface (torrid, two temperate and two frigid) that we also use today.

3. HYDRAULIC MECHANISMS AND DEVICES

The foundation of hydraulics after Archimedes led to the invention of several hydraulic mechanisms and devices with significant contribution to diverse applications from lifting of water to musical instruments. Although in antiquity several devices were in use to lift water to a higher elevation, the first device that deserves the characterization pump with the modern meaning is Archimedes's helix or water-screw. The invention of the water screw is tied to the study of the spiral, for which Archimedes wrote a treatise entitled *On Spirals*, in 225 BC. This Archimedes's invention is first mentioned by Diodorus Siculus (first century BC; Bibliotheke, I 34.2, V 37.3) and Athenaeus of Naucratis (*ca*. 200 BC; Deipnosophistae, V) who transferred an earlier text (of the late 3rd century BC) by Moschion, describing a giant ship named Syracusia.

This pump is an ingenious device functioning in a simple and elegant manner by rotating an inclined cylinder bearing helical blades around its axis whose bottom is immersed in the water to be pumped. As the screw turns, water is trapped between the helical blades and the walls, thus rises up the length of the screw and drains out the top (Figure 1).

Figure 1. Archimedes's water screw in its original form as depicted in an Italian stamp (not quite correctly from a technical point of view) along with a bust probably representing Archimedes (from http://www.mcs.drexel.edu/~crorres/Archimedes/Stamps/).

Figure 2. Archimedes's water screw in its modern form, as implemented in the wastewater treatment plant of Athens (one of 5 screws that pump 1 million m^3 per day).

As mentioned by Athenaeus of Naucratis, the first use of the water screw must have been done by Archimedes himself to remove the large amount of bilge-water it would accumulate to the large ship *Syracusia*. There is historical and archaeological evidence that in antiquity the use of the water screw was propagated to all Mediterranean countries as well as to the east up to India. It was rotated by a man or a draft animal. Its uses range from irrigation (e.g. in Egypt) to draining of water in mines (e.g. in Spain). In its original form, the screw of Archimedes is still used even today in some parts of the world. For example, farmers in Egypt and other countries in Africa use it to raise irrigation water from the banks of rivers.

A modern version of the screw that is in industrial use today has two main differences from its original one: it is powered by a motor and the screw rotates inside of the cylinder rather than the entire cylinder being rotated; the latter modification allows the top half of the cylinder to be removed, which facilitates cleaning and maintenance. The modern screw is the best choice for pumping installations when water contains large sediments or debris, and when the discharge is large and the height small. Thus, the screw is used today mainly for pumping wastewater and stormwater runoff (Figure 2). It has been also used in other types of applications such as pumping of oil and supporting blood circulation during surgical procedures.

Another pumping mechanism, the force pump was invented by the engineer (initially barber) Ctesibius of Alexandria (*ca.* 285-222 BC) who was also the inventor of other instruments like the hydraulic clock and hydraulis, a hydraulic musical instrument. The force pump has been described by Philon Byzantius (Pneumatica), Hero of Alexandria (Pneumatica, I 28) and Vitruvius (X 7, 1-3). This pump is composed of two cylinders with pistons that were moved by means of connecting rods attached to opposite ends of a single lever. The force pump was used in many applications, such as in wells for pumping water, boats for bilge-water pump, basement pump, mining apparatus, fire extinguisher, water jets, etc. Yet another pumping device, the chain pump was invented in Alexandria by the engineer Philon Byzantius (260-180 BC). This was a set of pots attached to a chain or belt that was moved by a rotating wheel. Several pneumatic devices and mechanisms including a steam boiler, a reactive motor, the organ (harmonium) and several jet springs have been invented by Hero of Alexandria (4, 5, 6). Most were based on the siphon principle, or more generally, the combined action of air and water pressure. Ctesibius, Philon Byzantius and Hero where the three most famous engineers of Hellenistic Alexandria, whose studies mark a significant progress in hydraulics. This progress allowed the installation of advanced water supply systems like that of the citadel at Pergamon, in which pressure pipes (probably made of metal) were implemented. It also led to the great advances in the art of aqueducts during the Roman period.

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