Hydrologic and Hydraulic Science and Technology in Ancient Greece

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INTRODUCTION

The approach typically followed in problem solving today is represented by the sequence in the order: Understanding—data—application. However, 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 started in Greece as early as ca. 2000 B.C.. Specifically, in the Minoan civilization 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 B.C., Greek philosophers developed the scientific views of natural phenomena for the first time ever. In these, hydrologic and meteorological phenomena had a major role, given that water was considered by the Ionic school of philosophy (founded by Thales of Miletus; ca. 624–545 B.C.) 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 Archimedes' water screw pump.

SCIENTIFIC VIEWS OF HYDROLOGIC PHENOMENA AND HYDRAULICS

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

However, long before Plato, as well as much later, several Greek philosophers had developed correct explanations of hydrologic cycle, revealing 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 B.C.) 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 (5th century B.C.) recognizes that all waters originate from sea. Anaxagoras, who lived in Athens (500–428 B.C.) to Empedocles (ca. 493–433 B.C.) and is recognized equally as the founder of experimental research, clarified the concept of hydrologic 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 complementing Anaximenes' theories; his theory about thunders, which was against the belief that they are thrown by Zeus, probably cost him imprisonment (ca. 430 B.C.). In particular, he correctly assumed that winds are caused by differences in the air density: the air, heated by the sun, moves towards the North pole leaving gaps that cause air currents. He also studied Nile's floods and attributed them to 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 B.C.), who seemed to have clear knowledge of hydrologic cycle and its mechanisms.

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

Archimedes (287–212 B.C.), 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 B.C., 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. He is recognized[3] as the first person 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 B.C.), 1800 yr before Copernicus (who admits this in a note). Aristarchus also figured out how to measure the distances to the Sun and the Moon and their sizes. In addition, not only did ancient Greeks know that Earth is spherical, but also Eratosthenes (276–194 B.C.) calculated, 1700 yr 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, the geographer Strabo (67 B.C.– 23 A.D.) had defined the five zones or belts of Earth's surface (torrid, two temperate, and two frigid) that we use even today.

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 past several devices were in use to lift water to a higher elevation, the first device that had the characteristics of a pump with the modern meaning is Archimede's helix or water screw. The invention of the water screw is based on the study of the spiral, for which Archimedes wrote a treatise entitled *On Spirals*, in 225 B.C.. This invention of Archimedes was first mentioned by Diodorus Siculus (first century B.C.; Bibliotheke, I 34.2, V 37.3) and Athenaeus of Naucratis (ca. 200 B.C.; Deipnosophistae, V) who transferred an earlier text (of the late 3rd century B.C.) by Moschion, describing a giant ship named Syracusia.

This pump is an ingenious device which functions 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, and thus rises up to the length of the screw and drains out at the top (Fig. 1).

As mentioned by Athenaeus of Naucratis, the first use of the water screw must have been by Archimedes himself to remove the large amount of bilge water that would accumulate on the large ship *Syracusia*. There is historical and archaeological evidence that in past 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 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 the cylinder rather than the entire cylinder being rotated;

Fig. 1 Archimedes' 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/).

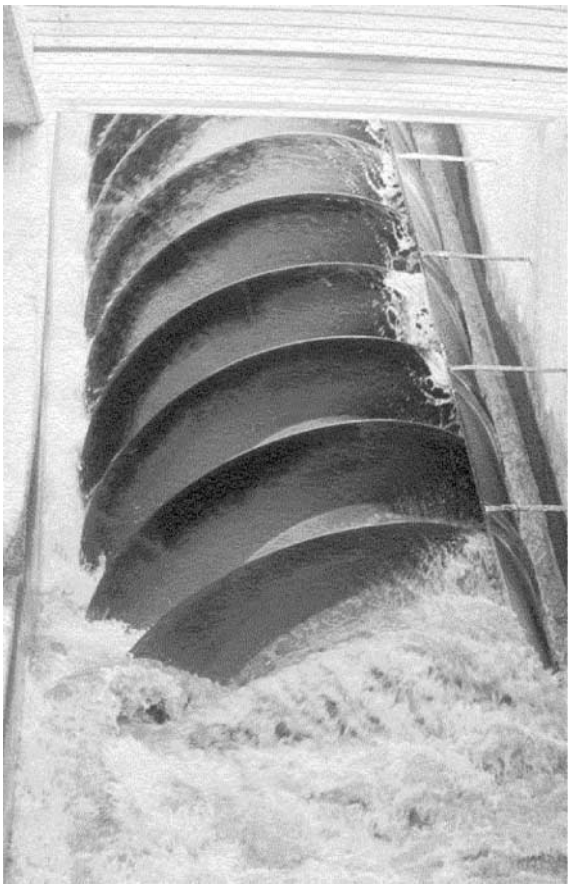

Fig. 2 Archimedes' water screw in its modern form, as implemented in the wastewater treatment plant of Athens (one of nine screws that pump 1 million m^3 per day).

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 (Fig. 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 engineer (initially barber) Ctesibius of Alexandria (ca. 285–222 B.C.) who was also the inventor of other instruments such as 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, and water jets. Yet another pumping device, the chain pump was invented in Alexandria by an engineer Philon Byzantius (260–180 B.C.). This comprised 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.[4–6] Most of them were based on the siphon principle, or more generally, the combined action of air and water pressure. Ctesibius, Philon Byzantius, and Hero were the three most famous engineers of Hellenistic Alexandria, whose studies mark a significant progress in hydraulics. This progress allowed 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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