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Keynote Address

The dawn of hydrology and water management in Ancient Greece

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Abstract

In the period between the 7th and the 3rd centuries B.C. the Greek philosophers and scientists made significant contributions to the science of hydrology. Motivated by a strong desire to explain the natural phenomena Thales, Plato, and Aristotle as well as their contemporaries sowed the first seeds of hydrology as a science. On the other hand architects and engineers of the time practised remarkable technical skills in constructing and operating various elements of water systems that were emphatically required in the growing urban areas.

1 Introduction

The period between the 7th and the 3rd centuries B.C. can be characterized as the most eventful in the history of ancient Greece. The dramatic social and political changes that took place during this era of Hellenic Civilization had a distinct impact and a great influence on the development of many branches of sciences. Among them the water science has an important place concerning both theoretical issues and practical innovations. The establishment of basic principles of the water science was mainly driven by a new philosophic approach: not only to control - as it was done during previous civilizations - but also to understand nature. The contribution of Greek philosophers to the development of the water science, or the science of hydrology in particular, is marked by the fact that for the first time man attempted to give thought to natural causes rather than divine ones and also pursued knowledge for its own sake. This is why this period has been recognized as the dawn of hydrology. It should, though, be emphasized that, due to the lack of sophisticated measuring instruments, most questions posed and answered at that time were qualitative rather than quantitative.

During the same period the growth of certain important cities led to the application of traditional methods of finding and collecting water supplemented by increased technical skill in the transport and storage of water. This notable dexterity sustained all large scale projects that were necessary, due to the close relationship between water management and urbanization.

From the above it can be seen that, for the period studied, the science of hydrology and the practices of water management were not actually related to each other. As a consequence, these subjects can not be dealed but separately, and this is how it is done in this paper. It is also inevitable that the discussion about scientific ideas will be concerned with persons, while reference to water management practices will be mainly focused on the construction and use of elements of water systems.

2 The contribution of Greeks to the science of hydrology

The age of the Ionian School

The first systematic approach to water science dates back to the birth of the Ionian School in Asia Minor in about 600 B.C. [1]. Using the empirical knowledge of pre-Hellenic civilizations, mainly from Egypt and Mesopotamia (where the development of water systems from the three major rivers the Nile and the Tiger and Euphrates proved to be a valuable source of information), the Greek philosophers succeeded in establishing a small but important number of principles of water science. It is in this period when for the first time every single physical phenomenon becomes the subject of discussion by accepting its natural causes. In *The clouds*, one of the most known comedies of the Athenian playwright Aristophanes, written in 423 B.C., there is a characteristic dialogue between Strepsiades and Socrates where the concept that rain was sent by Zeus is commented in a very caustic way.

Thales of Miletos, one of the Seven Wise Men of ancient times and founder of the Milesian School, is acknowledged as the first Greek mathematician and astronomer. According to Aristotle, the fame of Thales came mostly from his abilities to learn about new elements and to apply his knowledge to practical advantage. Thus, at the threshold of physical philosophy, Thales set forth the following two basic statements: a) the earth floats on the water, and b) water is the original substance and it is therefore the material cause of all things. Anaximander of Miletos, who was a contemporary of Thales, Xenophanes of Colophon, and Anaxagoras of Clazomenae, who was the last of the renowned Ionian philosophers (died in 428 B.C.) had all contributed to explanations of phenomena like the origin of clouds, rain, springs and streams.

Herodotus of Halicarnassus, the father of history, had a particular interest in hydrologic phenomena. He, like his contemporary Anaxagoras, studied the river Nile mostly impressed by the regularity of its floods. It is worth noting that, during the period studied, various theories on the origin and rise of the 'legendary' river were put forward by a sizeable number of Greek philosophers, historians and geographers including Oenopides, Diogenes, Democritus, Ephorus, Eratosthenes, Strabo, and of course Aristotle ([1], [2]).

The age of Plato and Aristotle

The statement 'Let no man ignorant of geometry enter here' that was inscribed across the top of Plato's Academy (founded about 387 B.C. in Athens) is indicative of the scientific thought of the great philosopher who professed a great love for mathematics. Most of Plato's scientific work is included in *Timaeus* but reference to hydrologic subjects was made also in other dialogues, like *Critias* and *Phaedo*. On the other hand, Plato had an interest in water laws and this can be located in his most lengthy as well as practical work, *The laws*, where his concepts, ideas and proposals regarding water use permits, water management - especially in case of water deficiency - and penalties following water pollution could be easily compared to relevant modern theories and practices.

The most discussed concept of Plato - discarded and even derided later among others by his own pupil Aristotle - concerns with the origin of rivers and springs. Plato accepted the hypothesis on the existence of Tartarus, the Homeric ocean, which he imagined to be a huge subterranean reservoir that penetrated the entire earth and from which flow all waters to the rivers and streams and vice versa in a continuous way. An alternative explanation of the origin of rivers and springs, which appears in *Critias*, shows that Plato could be also credited with the pluvial concept of the same phenomenon, a view most probably based on acute observation [3].

The concept of Aristotle of Stagira of the universe is somewhat similar to that of Plato and Pythagoras, the great mathematician from Samos. As he believed in five elements, each of which credited with two of the four qualities (i.e. cold, hot, dry, and humid), Aristotle defined water as the 'earthy' element that has the qualities of cold and humid. His interest in hydrologic phenomena related to rain, snow, hail, wind, ocean and the origin of rivers and springs appears in portions of his gigantic work *Meteorologica*, the first treatise on meteorology. This work, written in the 4th century B.C., was not confined to the classical meteorology but dealed also with astronomy, chemistry, geology and physics. After all the greatest mental disciplinarian can be surely considered as the watershed of the two studies, philosophy and science, as after him it was noticeably harder not to feel that the two studies were incompatible.

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Although Aristotle, like his predecessors, did not have a clear concept of the difference between air and vapour, he recognized the cyclic movement of water between earth and atmosphere as well as the processes of evaporation and water vapour condensation. By considering facts like the immense size that a single subterranean reservoir should have, the losses due to evaporation and the non-uniform direction of all rivers, Aristotle rejected the concepts of the origin of rivers and springs propounded by Anaxagoras and his teacher Plato. Besides, the great Greek philosopher formulated his own concept on the phenomenon through three different explanations: a) rainfall and percolation, b) subterranean condensation of air (vapour) into water, and c) condensation of rising vapours.

Theophrastus, pupil, collaborator and successor of Aristotle to the headship of Lyceum, was a very prolific author on many sorts of subjects. Unfortunately very few fragments of his original works were preserved and most of what are available at present owe their existence to Syrian and Arabic translations. In hydrology Theophrastus began where his master left off and he finally managed to be considered as the first man to clearly understand the hydrologic cycle.

The main conclusion drawn for the period studied is that the Greek philosophers and scientists, using the least of measuring instruments and based on personal acute observations, achieved to establish a way of thinking and an approach to knowledge regarding the basic hydrologic phenomena that greatly contributed to the science of hydrology. Thus, the concepts and ideas in their preserved work (see Table 1) can, without any hesitation, be considered as the first seeds of hydrology as a science.

Table 1. The most important works of Greek philosophers and scientists with references to hydrological subjects

Aristotle	*De coelo (On the heavens)*
Aristotle	*Metaphysica (Metaphysics)*
Aristotle	*Meteorologica (Meteorology)*
Herodotus	*The history*
Plato	*The laws*
Plato	*Timaeus*
Plato	*Critias*
Plato	*Phaedo*
Strabo	*Geographica (Geography)*
Theophrastus	*De ventis (On winds)*
Theophrastus	*De signis tempestatum (On weather signs)*

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3 Water management in ancient Greek cities

The demographic history of Greece during the first millennium B.C. is a subject that is still under study by using information from various sources, especially archaelogical excavations. Recent evidence from intensive surveys indicates drastic fluctuations in human population density associated with an apparent alternation between nucleated and dispersed settlement. As far as water management is concerned, the steep rise in population and the urbanization during the period studied are two important factors that greatly influenced the design and construction of the water systems.

Although the rise in population and maybe the cultural and economic development in the first millennium B.C. can be also related to significant improvements in agricultural technology and relevant water practices [4], we will restrict our discussion to urban water systems of the time because the relevant historic evidence is much more justified due to the numerous preserved elements of these systems.

Water transport systems

The water supply and distribution systems in Greek cities were given careful attention in order to assure both survival and amenity. Especially in big and important cities the water systems were constructed using up-to-date and also intricate techniques. In addition, it is worth noting that the existing close cultural and economic relations between mother-cities and their colonies resulted to the transfer of such technologies outside Greece. A typical example is the case of the city of Corinth and its colony Syracuse [5].

The growing sophistication of the technology employed to build various water projects during those years was characteristically dependent on the knowledge and the skill of the people who were in control of them. Thus, in the 7th century B.C. the tyrant Theagenes at Megara had full responsibility in building his famous fountainhouse, but later, in the 6th century, Peisistratos, the tyrant of Athens, let a board of commisioners to construct the aqueduct that bears his name. As the time passed engineers and architects took on all such works, like in the case of the tunnel at Samos, designed and constructed by the architect-engineer Eupalinos of Megara. Finally, in the 4th and 3rd centuries B.C. the construction of water lines was assigned to proper businessmen/contractors while their alignment had to be approved by building commissioners [5]. Nevertheless, the Greeks were rather 'practical' engineers so that their water lines, aqueducts etc. were built without any conscious applications of physical principles, but mostly by laying down practical ones.

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In early years properly enlarged natural channels served as aqueducts, but later Greek engineers improved the traditional knowledge to construct long distance water lines by implementing new methods, i.e. by diverting streams, waterproofing tunnels and even including pressure pipe lines (siphons) in the systems. Of the first siphons installed and functioned were those for the water supply of the cities of Syracuse in 450 B.C. and Smyrna and Pergamos in the 3rd century B.C. Selecting some from the renowned water systems of ancient Greek cities - mainly due to their aqueducts - we will refer in the following to those of Corinth and Syracuse, Athens, and Samos.

Peirene Fountain was the most important source for the water supply of the city of Corinth. The fountain, situated centrally in the agora area, was supplied by water from a couple of tunnels, the east and the west. The second one had a number of short branches to collect water from several small streams that crossed its line. Maintenance of both tunnels was facilitated by well shafts opened along their length which, icluding all sorts of channels, was about 3500m in total. On the other hand the city of Syracuse had a number of water lines, among which the most known is the Galermi Aqueduct that was 25km long and is still flowing.

The Aqueduct of Peisistratos is considered one of the greatest water works in ancient Athens and it was used for many centuries as the main water transport element for the supply of the historic city. Its beginning was in the valley of river Ilissos and water was collected from the river as well as from the mountainsides of Penteli. Where technically possible the aqueduct was a trench cut in the rock with depth 1.30-1.50m and width about 0.65m, while in softer grounds it consisted of clay pipes supported by carved porous stones. The pipes had a diameter of 0.19-0.22m and at every 30-40m along their lines there were air-shafts with a depth up to 12m. Cleaning of the pipes was possible through small openings which, under normal flow operations, were sealed with clay plugs. This sophisticated system is indeed a substantial proof of the high technical skill of ancient Athenians.

The most significant element of the aqueduct of Samos, that functioned for about 1000 years, is the tunnel that carries the name of its engineer, Eupalinos. The tunnel with a length of 1036m was the middle part of the 2400m aqueduct which was used to transport water from the source to a fountainhouse in the city of Samos at a rate of approximately $400m^3$/day. The cross-section of the tunnel had dimensions of 1.75mx1.75m with the ditch being opened on its floor. Because the whole tunnel was almost horizontal the ditch had a variable depth 3.5-8.5m in order to ensure a fixed slope at its bottom of about 0.5%.

Springs and fountains

The well-known springs and fountains of ancient Greece owe their fame either to the fact that they were held sacred or to their monumental character. Apart from the decorative elements (e.g. colonnades, facades and courtyards), the fountains were equiped with large reservoirs used to store water that was drawn usually from smaller draw-basins. In Mycenae, one of the most known pre-historic Greek settlements, the wells and cisterns of the acropolis could not assure the water supply, especially in a time of siege. The Persia Spring, built in the 13th century B.C. to supplement the existing sources, is a remarkable work of that old time due to its special elements, like the covered secret staircase (99 steps) that led to the underground reservoir.

The Castalia Fountain was located near the oracle at Delphi and it was therefore of a sacred nature. Pythia and the priests used to go to the fountain to clean themselves before entering the temple of Apollo for a sacrifice to the gods, a divination or any other service. The fountain was constructed by porous material at the time of the First Sacred War (600-590 B.C.). Around 460 B.C. a covered aqueduct was carved on the rock and water was stored in a 6.5x1.5m basin built of stone. From there the water was drawn and conveyed to four taps decorated with lion heads.

The city of Corinth was famous for its fountains, among which the Cyclopean Fountain, Peirene and the Glauke Fountain date from the 6th century B.C. and are all located within or very close to the agora. The archaeological evidence shows that, even from then, the Corinthians certainly knew a lot about spring and fountain houses, regarding both their construction techniques and decoration methods [5].

Domestic arrangements and public baths

Evidence from wells and cisterns exist even from the early Neolithic times. Practically in every major settlement archaelogical surveys have brought into light various types of these arrangements used in private as well as in public buildings. A mixed system of water supply, that is the old methods of individual type (wells, cisterns, and springs) gradually supplemented by new methods like the public water lines, assured availability for domestic use, for industry and for public baths. Survival and amenity were of course the primary tasks of the developed water systems, but their sophisticated employment, e.g. in re-using waste waters to irrigate crops, was not a rare activity during that period.

Public baths are known from the pre-historic period, with typical examples those in Cnossos and Tiryns. In the classical period baths were used in private dwellings but since the 5th century B.C. public baths started to become very popular, particularly in locations close to athletic complexes. As the Greek cities grew - and so did their water transport systems - more bathing establishments were connected to the main aqueducts. Still, far more developed public baths can be found only later in the Hellenistic Period and especially during the Roman Civilization.

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