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The Evolution of Water Supply Throughout the Millennia: A short overview

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21.1 Introduction

The importance of water for life, human prosperity and culture development was understood very early in all civilizations. In the initial stages of the civilizations this understanding had been depicted in mythologies and the natural forcings producing the water cycle had been represented by gods and goddesses. The introductory four chapters of these book deal with the evolution of the understanding of the water as a substance, its circulation on earth, and its quantity and quality.

All ancient civilizations had water gods and goddesses showing the significance of water to all of them, as described in **Chapter 1**. The variety among different civilizations of the forms and the features of the gods of water is impressive, illustrating the different perceptions among civilizations on the mechanisms of water cycle. What is common though in almost all civilizations is the popularity and strength that the gods of water enjoyed.

In **Chapter 2,** the evolution of urban water management in ancient civilization is discussed. During the Neolithic age (*ca*. 10,000-3,000 BC), the first successful efforts to control the flow of water were driven by agricultural needs (irrigation). During the Bronze Age, the first water treatment attempts to improve water quality have been made. An ancient Hindu source presents, probably, the first water standard, dating 4000 years ago: It dictates that the dirty water should be exposed to the sun and then a hot copper bar to be inserted seven times in it, followed by filtration, cooling and storage in a clay jar. Gradually, as the small settlements grew to cities, the sources of fresh water within the boundaries of the city were not sufficient for the needs of the larger population. Thus, additional water quantities had to be brought from sources outside the boundaries of the city. In Greece, the Hellenistic period marks significant developments in hydraulics, which allowed the construction and operation of aqueducts, cisterns, wells, harbours, water supply systems, baths, toilets, and sewerage and drainage systems. During the Roman period, the technological developments shifted to longer and bigger water transportation systems, namely aqueducts. The basic development in the Byzantine times was the construction of large scale cisterns.

Chapter 3 deals with the historical evidence on waterborne diseases and their prevention. The necessity of water treatment had been well understood by ancient peoples. It can be inferred from the writings of Hippocrates, the father of medicine, that water was considered an important issue for the public health. "Plagues" were described and in particular associated with the decimation of the Greek Army near the end of the Trojan War and with massive epidemics in Roman history. The understanding of the ability of pathogens to be transmitted from person to person was said to arise during the Plague of Athens, occurred in Athens in 430 BC, killing about 30 000 people.

Hypotheses have been developed on the etiology of diseases including influenza, smallpox, bubonic plague, typhus and Staphylococcus. However, even in 1860, while clean water was known to be important, the role of contaminated water in disease transmission was not understood and there were few options for treating water. Sanitation and hygiene were the order of the day due to aesthetic reasons (bad odours) which were still associated with ill health. In recent years, advancements in water treatment technologies and engineering have made outbreaks of water-related diseases more of a rarity for those people fortunate to have sewage treatment and access to drinking water that is consistently clean and safe. However due to a combination of factors (including conflicts, natural disasters, poverty and treatment failure), illness and death due to diseases such as cholera, typhoid and cryptosporidiosis continue to affect millions of people throughout the world.

In Chapter 4, the availability of water, especially in Near and Middle East, is examined, along with characteristic examples of water supply practices from ancient Greece. At the earliest stage, people performed all activities near rivers and streams and the surface water was the main source of water supply. Groundwater was also exploited, particularly for water supply. The springs are the natural emergence of groundwater, but drilling wells was also common. Egyptians developed drilling systems in rocks as early as 3000 BC. In Minoan Crete, wells (with a depth of 10-20 m and diameter less than 5 m) and springs were used for water supply. The groundwater exploitation in Cyprus started 7 000 years ago and it is connected with the oldest dug wells of the world. Ancient Chinese also developed a drilling tool for water wells, which in principle, is similar to modern machines.

21.2 Water technologies in different civilizations

Civilization prosperity and collapse are strongly related to availability of water and infrastructures for its use. The Indus Valley civilization (3000-1500 BC) is thought to have collapsed because of the course shift of the Indus River and the continued salinization. Mohenjo Daro in the Indus Valley (Pakistan) declined after 2000 BC possibly due to climate change, river shifts, and water resources management problems. Droughts possibly caused the collapse of the Akkadian Empire in Mesopotamia in *ca*. 2170 B.C. The Minoan civilization declined possibly due to an earthquake damaging the terracotta pipes and other network devices and disrupting the water supply (Gorokhovick, 2005). In addition, the seismic activity could have influenced the hydrological conditions and probably disrupted the groundwater aquifers. Thus, the water supply from all aqueducts (Knossos, Malia, and Tylissos) and wells (Knossos, Palaikastro, and Zakros) were affected. Petra, the Nabataean civilization capital in southwestern Jordan, collapsed as a result of the disruption of the elaborate water supply systems caused by an earthquake on May of 363 AD.

In China, as rivers and canals usually pass through the cities, flooding was, historically, the main cause of collapse. A total of 27 floods occurred in Luoyang during the period of the Sui (581-618 AD) and Tang (618-907 AC) dynasties (**Chapter 8)**. After the fall of the Northern Song Dynasty, Kaifeng was severely damaged during the Yuan and Jin dynasties. Flood disasters were frequent after 1194 AD, when the Yellow River changed its course and flowed towards the southeast. From the Jin to the Qing dynasty, the Yellow River flooded Kaifeng six times and the nearby areas 40 times. Finally, the once prosperous Kaifeng fell into oblivion (**Chapter 8**). However, the extreme behavior of nature as a key element on the history of mankind, is best understood by studying the ancient civilizations in the American continent: crisis overtook all the classic civilizations of Mesoamerica (including the Maya), forcing the abandonment of most of the cities.

In most cases, no conclusive evidence on why civilizations collapse exist. However, of all natural disasters, the role of drought must have been, historically, the most underestimated. Drought differs from other natural disasters in the following points:

a) It affects greater populations than any other natural disaster.
b) It develops slowly and in concealment. It is thus difficult to determine its beginning and its end, and its effects accumulate over a long time and can persist for several years after its expiration.
c) Its social effects are less visible and extend over much larger geographic areas than other natural disasters (e.g. floods, fires, and earthquakes).
d) It is difficult to quantify its effects since drought rarely results in destruction of infrastructure.

In contrast, prosperity of civilizations is ever related to successful addressing of water-related challenges. Eleven chapters of this book provide characteristic examples from different civilizations.

Chapter 5 deals with water and water supply technologies in Ancient Iran. With the exception of areas close to rivers, the sole available resource for water is ground water. Therefore, ancient Iranians invented the qanats, through which, they were able to bring water from underground up to the surface without spending any energy thereby solving the problem of agricultural water supply. The history of the ancient dams in Iraq dates back to 3000 years and shows that ancient Iranians were among the pioneers in dam construction. In Iran, one of the greatest deeds of Darius the Great was the creation of a "Water Organization", whose head, called "Ao-Tar" or Water Master, controlled the qanats, dams, rivers etc. Other developments include subterranean water reservoirs, ice chambers and water mills. Water supply and drainage of the Persepolis complex were first built during the reign of Darius the Great (521 - 486 BC).
In Iran, over millennia, 22 000 qanat units were constructed, comprising more than 270 thousand kilometers of underground channels. In the 1960s, 75% of all the water used in that country for irrigation and domestic consumption was provided by such systems. Qanats were the symbol of sustainable development and operation of groundwater resources, whereas after the more recent expansion of wells as well as the intense use of pumps, these resources, which should be preserved for future generations, are unfortunately facing serious threats.

Over the centuries, the qanat technology was transferred to all civilizations and became known with different names such as 'karez' (Afghanistan and Pakistan), 'kanerjing' (China), 'falaj' (United Arab Emirates) and 'foggara/fughara' (North Africa). Despite this diffusion of qanat technology throughout the ancient world, the construction of similar structures called puquios in America (**Chapter 11**) indicates a parallel evolution of a similar technology from civilizations that did not communicate.

Chapter 6 deals with the development of water supply in Egypt, and the role of the Nile River in the civilization, life and history of the Egyptian nation. In 3000 BC, Pharaoh Menes began with the construction of basins to contain the flood water, digging canals and irrigation ditches to reclaim the marshy land. Also, he is credited for diverting the course of the Nile to build the city of Memphis. The Nilometers, which measured the water level in the Nile were the first hydrological instruments in the world. As a result of their continuous operation through the centuries, the Nile has offered the largest hydrological time series.

Egyptians suffered many losses due to yearly flooding of the Nile. As an effect of that, the first form of government appeared when the Egyptians organized their efforts under leadership of a single authority to avoid these disasters. As time passed, the leader (pharaoh) became more important with more power and influence on Egyptians.

Chapter 7 deals with the impact of climate changes on the evolution of the water supply works in the region of Jerusalem. The oldest water works date to the middle Bronze Age (ca. 1800-1500 BC). These water works were altered and extended in later periods. It is assumed that three main reasons dictated the nature of water works in Jerusalem from its earliest history until today: (a) The short-term climatic factor, namely the dry summer months and the occasional years of drought. (b) The long-term climatic factor of the past periods of wet and dry climates. (c) The need for security which dictated the building of the often fortified settlements on the peak of hills and thus creating the need for a secure access to the nearest water resource in the valley. In periods of warming, as happened throughout history, the move of the desert line north has caused aridization and desertion of cities. During such extreme periods of droughts, springs, particularly those fed by a local perched water table as in the region of Jerusalem, may have dried up and lead to the abandonment of the site. The main conclusion of chapter 5 is that warm climates spelled dryness and the first to be influenced were the small springs with a limited recharge area and small storage capacity. The discharge of bigger springs was also reduced once the warm and dry period extended over a longer period. Thus the bigger is the storage capacity the better chances are that the storage will mitigate the negative impact of dry periods.

In Jerusalem, the low topographical extension of the Eastern Hill was chosen for settlement instead of the higher level of the Temple Mount (or any of the other neighboring hills) mainly because it is nearer to the perennial Gihon spring. The oldest part of the city was built on the rather permeable Bina limestone. Thus the construction of cisterns had to wait until the invention of impermeable plaster sealing the bottom and the walls of these structures. The appearance of iron tools for digging water cisterns in bedrock and the invention of impermeable plaster were essential for the operational function of cisterns and aqueducts that enabled the early Israelis to settle to the hills.

In Chapter 8, the history of water supply of Chinese dynasties is extensively covered. Despite the unparallel for the ancient world scale of the cities, water infrastructures and their harmonization to the environment are remarkable. Site selection was of great importance as well. According to the book Guan Zi "the capital should be built either at foot of a great mountain or near a grand river; stay away from dry lands at high elevation in order to get enough water, and stay away from water at low elevation to prevent flood and save drainage and embankment."

Several ancient water supply schemes are still in use, or were at use until the 19th century, evidence to their remarkably advanced design and implementation. Among them, the famous Dujiang irrigation system, built in the 3rd century BC is still in use. In Nanjing, the 16 m high East Water Gate built in the 14th century is still well preserved today. Starting from the 13th century AD, the Old Town of Lijiang has built up a water supply system which met the needs of the inhabitants until the end of the 20th century. They are good examples of true sustainability over hundreds of years and are worth to considered and use as reference in modern city planning.

Karez, a system comparable to Persian qanat was developed in Turpan city. With the modern fast agricultural development and overuse of electrically pumped groundwater, the importance of karezes declined and many ran dry because of lowered groundwater levels. Since the end of the 1950s, modern water conservancy projects such as storage reservoirs, diversion works, and pumping wells increased the amount of available water and began to slowly replace the ancient, labour-intensive karez systems. However, sustainable water use and management has become an increasingly critical issue for the further development of the Turpan Region.

The abandonment of small-scale and traditional infrastructures that has occurred very recently is a big step backwards. Apart from qanats, practices and technologies (examined in other Chapters) that should be revisited include: (a) Water cisterns used to collect and storage rainwater; (b) Small-scale decentralized water supply systems; and c) Water recycling and reuse of water.

Chapter 9 deals with the evolution of water supply in the island of Crete, presenting a number of characteristic examples in selected sites extending from the early Minoan era to present times. During the Minoan era the principles of water supply and sanitation were developed and primitive distribution systems were designed and implemented in the palaces and other settlements in a rather small-scale, but in a cost-effective, decentralized and sustainable manner. The Minoan achievements were not totally forgotten during the Dark Ages. Possible interconnections with Mycenaean and Achaean Greeks had interacted on water supply developments both in Crete and in the mainland of Greece. The prehistoric technologies were further developed during the Hellenistic, Roman and Venetian periods, mainly at an enlarged scale of implementation.

Thus, Crete displays a diachronic continuity on development of water supply technologies. As climatic and geohydrological conditions in the island highly varied in history, water availability was spatially and temporal uneven. It is clear that water technologies, developed through the centuries, such as aqueducts, cisterns, wells and other systems were created and adapted to the local conditions and present an ecological sustainable system with a considerable potential in water supply.

Chapter 10 explores urban water management practices of ancient Greece, from the Archaic to the Hellenistic years. In the Archaic Greek antiquity cities tended to be located at dry places, at a distance from rivers or lakes. Under tyranny, cities grew significantly and the first large scale urban water infrastructures were developed. The period of democracy that followed, with its small-scale structures and its non-structural measures constitutes a lesson of sustainable management and marks the importance of the institutional progress in water management. During the Hellenistic period, the evolution of the "designed city" is mainly reflected on the scale of the projects, which results in water adequacy and more widespread hygienic water use. Some lessons learned are:

- City planning has to include urban water criteria; protection from floods should be a major consideration.
- The use of small-scale infrastructures, in parallel to the large-scale ones, is a big step towards sustainability and resilience. The principles and practices of sustainable water use should not be forgotten even in periods of water adequacy.
- Safety and security of water supply in emergency situations, including turbulent and war periods, should be kept in mind in our designs of urban water systems.

Chapter 11 deals with water supply in Pre-Columbian civilizations in Ancient Peru and South America. Among the environmental conditions that affect water affairs in these areas is the El Nino phenomenon. The institutional and organization framework have seen great developments as testified in the case of the Inca Empire "Tahuantinsuyo". Among the technological heritage of the Pre-Columbian civilizations, a very interesting case is the so-called puquios, a solution similar to Iranian qanats that indicates a parallel evolution of similar technologies in different places of the world.

Chapter 12 deals with the evolution of water supply in Cyprus and presents a number of characteristic examples in selected sites chronologically extending from the Neolithic age (*ca*. 8500 - 3900 BC) to present times. During the Hellenistic period, Cyprus was hit by strong earthquakes and several cities, towns and infrastructures were destroyed. Only ancient Amathus was less affected. After the destructive earthquakes, the cities of Cyprus were rebuilt. The Romans built their own structures on the foundations of structures from the Hellenistic period. To satisfy the water demand, water supply technologies such as aqueducts, cisterns, water conduits, chain-of-wells and other systems were developed. The trade with Egypt, Crete, and other Aegean islands had positive influences in the development of the water supply technologies.

In **Chapter 13,** the overview of the different elements of the Roman water supply systems that operated in Middle-East from the 1st century BC to the 7th century AD is presented. Romans mostly settled in Hellenistic cities with functioning water systems. In most cases Romans reworked and further developed these systems. What really differentiates during the Roman period is the scale of the projects, due to the ever increasing water demand. Romans, contrary to Greeks, had not sufficient documentation for their technologies: only a few Roman writings on water engineering practices have been preserved. Thus, the progress of that period is best demonstrated by the well preserved water supply systems throughout Middle-East. Examples include water transportation by aqueducts, water distribution by masonry channels and pipelines and water facilities, such as latrines, baths, toilets, fountains, and cisterns. The inverted siphons, practiced in Aspendos, represent a more sophisticated design solution. In Byzantine times, a decline of the quality of the water systems is commonly admitted. However, some counter examples exist.

Chapter 14 compares ancient Greek and Roman water systems and their elements, such as aqueducts, cisterns, reservoirs, water distribution systems, fountains, baths and thermae, and water use for recreational and/or environmental purposes. A continuation of water supply technologies between the two civilizations is observed. During the Roman period sound engineering principles, which were used by Greeks for centuries, were further extended basically by changing the scale of the hydraulics works. Comparison shows that water technologies in Minoan, Greek, and Roman civilizations are not too different from the modern practice, and that hydraulic works of the antiquity are characterized by simplicity, robustness of operation, and the absence of complex controls. Today, many of the water resources exploited in the Roman age are still in use.

Chapter 15 addresses water supply technologies of the pre-Columbian societies in the modern- day southwestern United States and in Mesoamerica followed by a discussion of the technology advancement during the post-Columbian era. Three examples from this chapter are very informative:

a) The Hohokam built the most complex irrigation system in the desert lowlands of the Salt-Gila River Basin, Arizona in and around the present day Phoenix, Arizona. They built more than 483 km of major canals and over 1126 km of distribution canals in the Salt River Valley, which have been identified. Hohokam irrigation systems consisted of three basic types of canals: main canals, distribution canals, and field laterals.

b) Chaco Canyon is situated in the San Juan Basin in northwestern New Mexico. The basin has limited surface water, most of which is discharged from ephemeral washes and arroyos. The water, collected from the side canyon that drained from the top of the upper mesa, was diverted into canals by either an earthen or a masonry dam near the mouth of the side canyon. These canals averaged 4.5 m in width and 1.4 m in depth; some were lined with stone slabs and others were bordered by masonry walls. The canals ended at a masonry head gate, where water was then diverted to the fields in small ditches or to overflow ponds and small reservoirs.

c) Xochicalco (in the place of the house of flowers), was located on hill top approximately 38 km from modern day Cuernavaca, Mexico. There were no rivers or streams or wells to obtain water, so that rainwater harvesting was the source of water. Rainwater was collected in the large plaza area and conveyed using drainage structures and drainage ditches into cisterns. From the cisterns water was conveyed to other areas of the city using pipes.

21.3 Some major cities

The next five chapters are devoted to urban infrastructure at some important sites, most of them in the Mediterranean. As most Mediterranean cities were located at a distance from large water systems, climatic variability played significant role in their evolution. However, during the Classical years and after, no major collapse has occurred. The consequences of climatic variability of a certain time period were less intense and were generally connected to the decline of a specific city on a certain time period. The main reasons for the sustainability of the Mediterranean cultures are:

- the existence of distributed urban systems;
- the combination of small scale and large scale infrastructures practiced in most cases;
- the wise site selection with respect to water resources (not close to large water systems in order to avoid floods, but with water adequacy); and
- the continuous adaptation to new needs.

As ancient Greco-Roman civilization has left us with more evidence (written and archaeological) than any other civilization, the non-stopping struggle to cover the demand on water is reflected in the history of cities like Athens (**Chapter 16**) and Rome (**Chapter 17**). The history of cities like Iraklion (**Chapter 18**) and Barcelona (**Chapter 19**) reflects the dependence of water supply infrastructures on the historical and cultural changes.

Chapter 16 investigates the water supply of Athens, Greece under rather adverse conditions, from 6th century BC up to the 6th century AD. Because of the inadequate capacity of springs and rivers in the vicinity of ancient Athens, the development of the underground water resources, became crucial. The water supply infrastructure was based on good geological knowledge, as testified by Solon's rules for wise management of ground water, as well as Plato's discussions on the geological past of limestone hills surrounding the ancient city. Thus, a systematic exploitation of the limited local water resources (springs, galleries and wells) in the city was complemented by transfer of surface and ground water from the surrounding mountainous Attica. The Athenian water system was characterized by (i) combination of small and large scale hydraulic works, (ii) sustainability and (iii) continuous adaptation to new needs (construction of several aqueducts to the city). Drainage and sewerage systems were developed in parallel to the water supply network. It is impressive that some elements of the water supply and drainage designed and constructed in antiquity in a practical and sustainable manner are operational up today.

As described in **Chapter 17,** Rome is another example of water technologies evolution, whose origin dates back to the Etruscan times. During the Roman Empire, several aqueducts were constructed (eleven of which are described). The historical development of water supply in Rome is not a local affair but it served as an example of universal dimension. The developments in Rome, including those in water technology and management, constitute an important part of the history of human civilization and were spread and assimilated in many parts of the world during many centuries.

In the case of the historical city of Iraklion, Crete, as described in **Chapter 18**, the historical developments of water supply in the antiquity were minor. Even during the Roman and Byzantine periods very little progress was made. On the other hand during the Venetian presence on the island the *Morosini* aqueduct of a total length 15.5 km, was designed and constructed within only 15 months. This was one of the major water projects for the city. At the time of the Ottoman occupation of Crete, with the exception for the short period of the Egyptian rule, there was no significant water supply work for Iraklion. After the Union of the island with Greece a serious progress in new water supply projects was made in Iraklion and the entire Crete.

The history of the Barcelona city (**Chapter 19**) seems to have begun in the Roman period in the time of the Roman Emperor Augustus, when the city was named as "Colonia Iulia Augusta Paterna Faventia Barcino". During that period several aqueducts were constructed. The aqueduct, which started at the Besòs River, was still used during the Late Empire and the Visigoth era. It was most probably abandoned in the 8^{th} or 9^{th} century. The evolution of Barcelona's water supply was highly influenced throughout the 18^{th} century due to the: (a) establishment of the Spanish Bourbon monarchy; and (b) the economic and demographic impulse experienced by Catalonia as the century advanced, with a clear repercussion on the urban expansion of Barcelona. Over the last two centuries, Barcelona's water supplies experienced several achievements facing the increased water demand.

Chapter 20 relates a different story, as it examines the evolution of water services in the Mexico City since the Aztecs time. It was conceived in the Aztec period directly due to the availability of water. The primeval city located on an island (Tenochtitlán), whose residents had access to sufficient water and planned their whole social and economic growth around this source, became Mexico City, a mega city suffering both from lack of water and flooding. During the Spanish rule, the Mexico City council created the water council to verify water permits and to collect water taxes but as well to operate the hydraulic infrastructure. In addition, the city council appointed a water judge, "to oversee the use of water", who was in charge of updating the use of Mercedes (e.g. the royal concession for industrial or agricultural use of water).