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Editorial

Evolution of Water Supply, Sanitation, Wastewater, and Stormwater Technologies Globally

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Abstract: This paper provides an outline of history of hydro-technologies in the west and the east. It is an overview of the special issue on "the evolution of hydro-technologies globally", in which the key topics regarding the history of water and sanitation worldwide, and its importance to future cities are presented and discussed. It covers a wide range of relevant historical issues, and is presented in three categories: productivity assessment, institutional framework and mechanisms, and governance aspects. This paper concludes by discussing the challenges on future research in this field of study.

Keywords: aqueducts-like qanats; cisterns; flood protection; lessons learned from the past; water history; water supply; wells; water resources management

1. Prolegomena

Most future facts are based on those in the past.
Euripides, 480–406 BC, Ancient Greek Tragic.

Humans have spent most of their lives as hunting and food gathering beings. However, it was only during the last 9000 to 10,000 years they discovered how to grow agricultural crops and tame animals. Such revolution probably first took place in the hills to the north of Mesopotamia. From there, the agricultural revolution spread to south Hellas, Sicily, and to the rest of Europe [1], and of course to the east (e.g., Indus Valley). About 6000 to 7000 years ago, farming villages of the Near East and Middle East became cities. During the Neolithic age (*ca*. 5700–3200 BC), the first successful efforts to control the flow of water were driven (such as dams and irrigation systems) due to the need for food. Thus, they were implemented in Mesopotamia and Egypt. Urban water supply and sanitation systems were dated at a later stage during the Bronze Age (*ca.* 3200–1100 BC) in Crete, Aegian islands, and Indus valley civilizations [2].

Hassan [3] stated that "the secret of the Egyptian civilization was that it never lost sight of the past". However, this is because of the unpredictability of the Nile River floods; and the production of grains brought about order and stability. The ancient Egyptians depend on the Nile not only for their livelihoods, but also believed the Nile to be a deific force of the universe, to be respected and honored if they wanted it to treat them favorably [4].

The first actual recorded evidence of water management was the mace head of King Scorpion (*ca*. 2725–2671 BC). This was the last Predynastic kings, and has been interpreted as a tool to initiate a ceremonial start in breaching the first dyke to allow water to inundate the fields or the ceremonial opening of a new canal. Mohenjo-Daro was a major urban center of the Indus civilization during the early Bronze Age. Thus, it is located about 400 km north of present-day Karachi, Pakistan. This planned City built around 2450 BC received water from at least 700 wells and had bathrooms in houses and sewers in streets as well as thermal baths [5]. The Mesopotamians were not far behind. The Sumerians, during the Bronze Age, and other age in Ancient Mesopotamia, provided an enormous amount of knowledge about themselves through cuneiform tablets. Water provided by the Euphrates and Tigris Rivers shaped their societies. The Sumerian epics referred to the effect of uncontrolled human activity on the soil and environment to be interpreted as the curse of God, of which we now understand as the environmental effects of intense irrigation [6,7].

At the east, the early civilization of China generated at the Yellow River basin which was characterized by the formation of permanent residences and agricultural development at around 4000 BC. Also, the flourishing age of early urban establishment started at the Spring-Autumn and Fighting-state periods (around 700~100 BC). However, there were many cities which were formed and developed in the Yellow River Basin during this period along with the establishment of a series of Kingdoms [8]. Accordingly, hydro-techniques were developed, and small scale and large scale hydro-projects were implemented in meeting the needs of domestic use, irrigation, flood control, transportation as well as the purpose of state control, *etc.* Furthermore, a well was the earliest way of using groundwater in the Yellow River basin which was dated back to 6174–5921 years [9]. Later, the local people also got rainwater for domestic use and for irrigation by cistern and pool; for example, the earliest cistern was discovered at Yangshao Culture Ruins [10]. Subsequently, these techniques have been used in China for thousands of years until the1970s.

At around 700–200 BC, along with the establishment of serial kingdoms at Centre China, a series of large scale hydro-projects were implemented to meet the demands of irrigation, population growth, defense of the city, and especially to enhance the power of the state. The typical large scale hydraulic project in this period was classified as aqueduct, dam, dyke and canal [11]. For example, Grand Canal Jing Han (1797 km of length) was started during the 5th century BC, the Zhengguo Aqueduct was built in 246–255 BC around 300 km for length of irrigation, Ling Canal was built in 219 BC to connect the basins of Pearl River and Yangtze River for transportation, and basically dykes were built for urban protection of flood which resulted to the establishment of several cities close to the Yellow River. These hydraulic projects greatly increased the agricultural development and enhanced the power of the kingdom. Consequently, the Qin Kingdom (221–207 BC) became the most powerful state that depended on their great hydraulic achievements, and later established the first united empire of China. In Han Dynasty (202 BC–220 AD), the urban development reached one of the peaks of the urban history. The urban hydraulic techniques also greatly advanced the paradigm in Chang'an City, the capital of Han Empire. The model of urban water system included water supply, water storage, rainwater management, drainage which was created and implemented in this city. Thereafter, it also influenced the construction of most city's water system for two thousand years [12]. Subsequently, hydraulic projects have been implemented largely in China, and it crosses a wide geographic area. However, many of them have been functioning for two thousand years until today. In addition, the foundational principle of water management and hydraulic technologies were achieved during the ancient age, especially during the 2nd and 1st century BC.

Meanwhile, on the periphery of these areas (e.g., in Arabia and in the deserts of Iran, Pakistan, and India), food production through farming and nomadic pastoralism, hunting and fishing, were intensified as the various capacities of the desert environment was used more efficiently. However, oases are humankind's most important way of surviving in the arid regions of this planet [13]. Through oases, these groups ensured physical and economic survival in hostile but mineral-rich areas, and had become strategic in the Chalcolithic period and Iron Age. It is in this context that the technology of catchment's tunnels, a factor that permits the enormous spread of oases was introduced, they are known in Iran as "qanat" or "kareez", in Morocco as "khettara", and in Algeria as "foggara" [14]. This technique has been in use for thousands of years, over a vast area extending from China to Persia, Spain, and even Latin America [4].

Other great civilizations such as the Minoans and an unknown civilization located on modern-day Crete and the Indus valley respectively, flourished during the Bronze Age (*ca*. 3200–1350 BC). They had developed wonderful water systems, such as aqueducts, cisterns, filtering systems, sedimentation basins, rainfall-harvesting systems, terracotta pipes for water supply and sewage, and the sewerage and drainage systems. The contacts of Minoans with Egypt intensified from the period of the first palaces (*ca*. 1900–1700 BC). Therefore, this suggests that a possible influx of technology related to water, wastewater, and stormwater management in this particular era should be in existence. In addition, based on the similarities of hydro-technologies developed by Mesopotamians and Egyptians, Minoan, and Indus valley civilizations should possibly be put into consideration [15]. As the Minoans, Egyptians, and Indus valley civilization developed trade relations with the Greek mainland, they influenced the Myceneans (*ca*. 1600–1100 BC) and Etruscans (*ca.* 800–100 BC) in the west and ancient Indian, and the Chinese in the east. The Myceneans and Etruscans were the most direct ancestors of the later Hellenes. Thereafter, the cultural diffusion that resulted from trade contacts with the Hittite Empire and Egypt began to deteriorate. However, all these remarkable civilizations collapsed even with their advanced capabilities in providing water supply. The interesting question is whether or not water resources sustainability was a significant component for their failure [16].

Later in the Archaic (*ca.* 750–480 BC) and Classical (*ca*. 480–336 BC) periods, both historical sources and archaeological excavations provide evidences that water and wastewater technologies were advanced and widespread in Hellas. Although the Greeks built on the previous knowledge of hydraulics and water resources, they also failed. The advancement of urban water technology and management is illustrated by the aqueduct of Samos (known as tunnel of Eupalinos) and the Peisistratean for Athens [17].

The Romans replaced the Greek rule in most locations, inherited their technologies, and developed them further. Also, the Romans substantially increased the application scale and implemented water projects in almost every large city [18]. The Greek and Roman water technologies are not only a cultural heritage, but they are underpinning modern achievements in water engineering and management practices.

Also, management practices were integrated, combining both large-scale and small-scale systems that sustain cities for millennia. The durability of some of the systems which operated until the present times, as well as the support of the technologies and their scientific background by written documents enabled these technologies to be inherited by present societies despite the regressions that have occurred throughout centuries (e.g., in the Dark Ages) [18]. During the same period, Islamic cultures on the periphery of Europe, had religiously mandated high levels of personal hygiene, along with highly developed water supplies and adequate sanitation systems, which in several cases were the same old Greek and Roman facilities, preserved along the centuries [6,7].

Therefore, the aim of this study is to reveal and describe the cultural heritage in various regions of the world, and give a clear understanding of hydro-technologies which have contributed to the development of the existing technologies in water, wastewater, and stormwater management.

2. The Main Contribution of This Special Issue

The nine selected articles can be divided into three categories, which are the three main areas of the theme as follows: "Water Management included Stormwater in the past Civilization: Lessons learned", "Evolution of Water Supply based on Aqueducts", and "Hydro-technologies in Minoan and Etruscans Civilizations and Possible technological Links between ancient civilizations (e.g., Minoans, Mycenaeans, and Etruscans)".

(1). In the first category cisterns have played an important role in water supply in numerous settlements worldwide since the Neolithic Age. Some characteristic examples of cistern technology in a chronological manner extending from prehistoric times to the present are provided [19]. The examples of water cistern technologies and management practices may have some importance for water resource sustainability and water storage for the present and future. Cisterns have been used not only to store rainfall runoff water, but also to store water transported by aqueducts from springs and streams for the purpose of meeting water needs through seasonal variations. In addition, cisterns can also play an important role for sluice of the rainwater in order to protect urban areas from floods.

The protection of urban areas from the destructive action of streams (floods, erosion, and sedimentation) is another case of application of hydraulic and water management technologies. Such techniques are also necessary in the development of agricultural areas, by taking into account that the most fertile areas are the flood plains of rivers. As mentioned above, small-scale projects (e.g., cisterns) of the latter type could play an important role in protecting urban areas. Here, we presented another example from Japan where flood management concepts and practices used in China during the Western Han Dynasty (206 BC–24 AD) were used during the Edo period of Japan (1603–1868). This concept is based on redirecting a river course in order to gain sufficient flood retarding capacity [20]. Independently of applying this practice either coincidentally or intentionally, it is a good example of how we could learn from the past. In modern times, the management of flood retarding basins differs fundamentally between China and Japan. In addition, this study investigates the differences in emergency evacuation practices between China and Japan. This is the first study to highlight the link between a Chinese concept and a Japanese practice that have development separately by more than 1000 years [20].

Furthermore, areas under scarcity of surface water (e.g., Palermo Plain), led the inhabitants to use groundwater for both irrigation and domestic usage. Other times, it is done through complex but sustainable hydraulic system. Vertical and horizontal wells convey water towards gardens and public fountains making the Arabic Bal'harm (Palermo) a flourishing town. Today, visitors could imagine that there is a wide and varied cultural heritage of underground cavities hidden in the basements where water flows in intricate networks fed from numerous underground springs. Only in recent years was a part of this system brought to light. Moreover, the city still has a wide and fascinating water management system based on distribution system consisting of irrigation basin, ingenious hydraulic machines named *senie*, and distribution chessboard of irrigation and drinking water canals [21].

Past water management practices could be applicable in modern times especially in regions under water scarcity. In Shanxi and Shaanxi provinces in China which are facing serious water shortages, the local societies took over water management and gradually formed a local self-government system for the water resources. This local self-government system for water resources is decentralized, and is very similar to those used during the Ming and Qing dynasties. This water management system played a positive role in mobilizing the participation of members, preventing opportunistic behavior such as free riding and rent seeking, while decreasing the probability of water conflicts and the costs of litigation [22]. In the study, the major concepts of this water management system and the problems that faced those systems were analyzed. Hence, this will provide a warning from history for modern society which was reported. In conclusion, smooth relationships and the correct allocation of functions between the state, elites, and ordinary peasant is perhaps an effective choice for modern water management in China and possibly elsewhere.

(2). In addition to cisterns and wells, aqueduct technologies have played an important role in water supply since the prehistoric times in numerous parts of the world. These hydraulic works were used by several civilizations to collect water from surface and underground springs, and surface streams to transport water to settlements, sanctuaries, and other targeted places [18]. Several civilizations worldwide have developed water transport systems independently, and have brought it to high levels of sophistication. The Minoan hydrologists and engineers were aware of some of the basic principles of water sciences, and the construction and operation of aqueducts. These technologies were further developed by subsequent civilizations [14]. Consequently, such improved technologies, including underground aqueducts (aqueducts-like qanats) were constructed by the Hellenes, and especially by the Romans. Thus, the Romans dramatically increased the application scale of these structures, in order to provide the extended quantities of water necessary for the Roman lifestyle of frequent bathing [18].

Historically, the aqueduct-like qanat technology was developed by Persians in the *ca*. middle of 1st millennium BC, and later spread towards Arabian Peninsula and Egypt. The expansion of Islam led to diffusion of qanats in the Mediterranean and central European countries [14]. These technologies were not improved, but survived through Byzantine and early medieval times. Later, the Ottomans adapted older techniques, reintroducing large-scale aqueducts to supply their emerging towns with adequate water for religious and social purposes. However, our ancestor's wisdom, experience, and knowledge could still play an important role for sustainable water supply both in developed and developing countries, either presently or in the future. Some of these technologies (e.g., aqueduct-like qanat) are characterized by its durability and sustainability, and are still in use in several parts of the world [14,18].

(3). As the third theme, possible interconnections among neighboring civilizations have been suggested [15]. Such possible links among Minoans (*ca.* 3200–1100 BC), Mycenaean (*ca.* 1600–1100), and Etruscan (*ca.* 800–100 BC) civilizations have been reported [23]. Also, there is a high contact of Mycenaean with both their eastern (e.g., Cypriots, Levant's, and Minor Asians), western (e.g., Sardinians, Sicilians, and Iberian Peninsula), and southern neighboring civilizations (e.g., Egyptians) (http://en.wikipedia.org/wiki/Mycenaean_Greece). Several similar hydro-technologies such as water harvesting and distribution systems, cisterns, groundwater and wells, as well as drainage and sewerage systems among those civilizations were indicated [23]. The long-term sustainability of Minoan cisterns is evidenced by the fact that this technique is still practiced today in the rural areas of Crete, Hellas. In addition to cisterns, wells, aqueducts, water distribution systems, and drainage and sewerage systems have been used, and has enjoyed wide-spread usage during the Mycenaean and Etruscan times [23].

3. Challenges and Prospective

It is well documented that most of the technological developments relevant to water supply and wastewater are not the achievements of present-day engineers, but they date back to more than five thousand years ago in prehistoric world. These developments were driven by the necessities to make efficient use of natural resources, to make civilizations more resistant to destructive natural elements, and to improve the standards of life. Thus, the very early settlements of humankind were established in temperate areas with sufficient water supply [17]. However, the study question is what and how can we learn from the past? With respect to the ancient water management principles and practices discussed in this study, it is important to examine their relevance to modern times and to harvest some lessons learned. Therefore, the relevance of ancient works will be examined in terms of the evolution of technology, technological advancement, design principles, and management principles [24].

The Evolution of Water Sciences. An important question to discuss is whether modern water technologies were derived from ancient technological achievements, or those achievements were totally forgotten especially during the dark ages, and had to be reinvented in modern times. The evolution of science and engineering is not linear, but is rather characterized by discontinuities and regressions. However, "bridges" from the past to the future have been always "built" in someway, albeit sometimes invisible in the present. Thus, such links among the ancient and neighbor civilizations were indicated [4].

Comparison of Ancient Achievement to the Modern Ones. Another issue that must be considered is the comparison of hydro-technologies in ancient times to that of the modern times. Certainly, many modern advances were not known in antiquity, such as the use of electromechanical equipment to pump water from deep wells, the use of plastic and concrete pipes in the transporting and distribution water systems, and the effective mechanical equipment for the construction of hydraulic works. Although to some extent, there are differences in the apparatus used today and the scale of applications, still there are no differences in the fundamental principles used. Even the lifestyle related to the hygienic standards of a civilization may not be a recent development. For example, flushing toilets equipped with seats resembling present-day toilets and drained by sewers has existed during Minoan times [17].

The scale of modern cities exceeds those of antiquity. This is also reflected in the scale of water infrastructures. As a result, a direct comparison is not possible. During the Roman period, the scale of aqueduct projects was highly increased as the Roman engineers learned how to effectively use concrete. Frontinus once asked if anyone "will ... compare the idle Pyramids, or those other useless, though much renowned works of the Hellenes, with these aqueducts, with these indispensable structures?". Pliny remarked that "if one takes careful account of the abundant supply of water for public purposes, for baths, pools, channels, houses, gardens, suburban villas, and the length of the aqueduct courses (the high arches, mountains tunneled, valleys crossed), he will confess that there has never been a greater phenomenon in the whole world" [25].

Durability of Ancient Hydraulic Works. Current-day engineers typically use a design period of structures of about 40 to 50 years, which is related to economic considerations. Sustainably, a design principle has entered the engineering lexicon within the last decade. Also, it is difficult to infer the design principles of ancient engineers. Nevertheless, it is notable that several ancient works have operated for very long periods of time, until contemporary times. For example, several underground aqueducts (or quanats) in Hellas and other parts of the world are in operation for millennia [14,18].

4. Epilogue

The main messages from this special issue reinforced several well-established notions about current research in the field of water supply and management. In the face of a number of major world challenges, new solutions must be sought for water management. As the 21st century continues, increased freshwater resources will be required in many locations to meet the needs of the increasing population, and the uncertainties and consequences of climate change. Demographic changes are the most significant challenges to present-day water and future challenges. What we can learn from ancient times is that using traditional knowledge could be a significant factor in solving water needs, especially in the developing parts of the world [7]. Furthermore, the historical examples of hydro-technologies given in this study have importance in today's water management. Some lessons learnt include:

a) It was stated that several ancient civilizations (e.g., Minoans and Etruscans) lived in harmony with nature and their environment, and their knowledge played an important role in sustainable water supply and the management of future cities.
b) Throughout history, a plethora of technologies (decentralized and environmentally friendly) were used for water supply and management for human survival and well-being.
c) The meaning of sustainability should be re-evaluated in the light of ancient public works and management practices. Technological developments based on sound engineering principles can extend the usable life of aqueducts. The use of small-scale infrastructures parallel to large-scale ones, greatly assists sustainability and resiliency. Also, the principles and practices of sustainable water use should not be forgotten even during periods of water adequacy. In

addition, safety and security of a water supply in emergency situations, including turbulent periods, should be kept in mind in the designs of urban water aqueducts.

d) A combination and balance of smaller scale measures (such as cisterns for water harvesting systems) and the large-scale water supply projects (such as aqueduct flows) were used by many ancient civilizations.
e) The ancient water technologies should be considered not mere as historical artifacts, but as potential models for sustainable water technologies for the present and for the future.
f) Finally, it should be noted that more than 2.6 billion people do not use improved sanitation, and 1.1 billion practice open defecation. However, there is a vast need for sustainable and cost-effective water supply and sanitation facilities, particularly in developing cities [26]. In addition, applicability of selected ancient water supply management systems (e.g., storage of rainfall runoff facilities) for the contemporary developing world should be seriously considered.

Conflicts of Interest

The authors declare no conflict of interest.

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