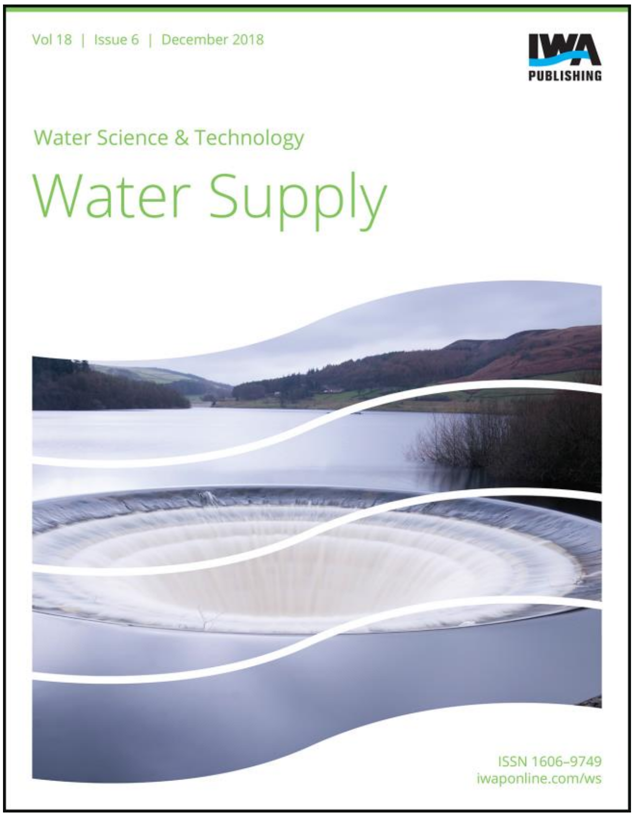

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Chinese and Greek ancient urban hydro-technologies: similarities and differences

Xiao Yun Zheng and A. N. Angelakis

ABSTRACT

The ancient civilizations of China and Greece, in the east and the west, have both subsequently deeply influenced other civilizations, regionally and across the world. Water management played a significant role in both civilizations and evidence demonstrates that many principles and technologies were generated by them, throughout both civilizations' long histories. As a result, they significantly influenced the ancient world broadly, some of which are still functioning up till this present time. This study comprises the following: methodology, hydrogeology, aqueducts and water impounds, water and wastewater mains, runoff management, agricultural irrigation, as well as the use of water for recreation purposes. Usually, urban hydro-technologies reflect a progressive situation in water management. Thus, both civilizations have also achieved urban water management. Therefore, for the purpose of understanding the role of water management in ancient civilizations and their similarities and differences beyond their geography, a comparison of urban hydro-technologies was selectively developed through the long history of the ancient Chinese and Greek civilizations, which also features the basic principle of water management in the human societies beyond these two civilizations.

Key words | Ancient China and Greece, stormwater management, wastewater, water management, water supply

Xiao Yun Zheng
Yunnan Academy of Social Sciences,
Kunming 650000,
China

A. N. Angelakis (corresponding author)
Institute of Iraklion, National Foundation for Agricultural Research (N.AG.RE.F.),
71307 Iraklion and Hellenic Union of Municipal Enterprises for water Supply and Sewerage,
Larissa 41222,
Greece
E-mail: *info@a-angelakis.gr*

INTRODUCTION

温故而知新

Revisit the past then to know the unknown

Confucius (551–479 BC), Ancient Chinese philosopher

Όμοια γάρ ως επί το πολύ τα μέλλοντα τοις γεγονόσι

Most future facts are based on those in the past

Aristotle (384–322 BC), Ancient Greek Philosopher

Both Confucius and Aristotle, the great ancient philosophers, teach that present and future events can be altered, and disastrous repeats can be avoided through knowledge gained from past events. China and Greece were the ancient civilizations in the east and west. Subsequently, both civilizations deeply influenced other civilizations both regionally and across the world. Water management played a significant role in both civilizations and it has been demonstrated that many principles and technologies were generated and developed by both the ancient Chinese and Greeks through out their long histories. As a result, they significantly influenced the ancient world broadly and some elements are still functioning up till this present time. This study comprises the following: hydrogeology, aqueducts and water impounds, water and wastewater mains, runoff management, agricultural irrigation, as well as the use of water for recreation purposes (Angelakis *et al.* 2005). It is worthy noting that water is a key dynamic in civilization's growth process worldwide and not just for human life. Due to the ancient civilizations in the east and west, a series of scientific and cultural fields were achieved originally in their ancient periods including

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hydro-technologies. Thus, the difference and similarities of the ancient water management and hydro-technological development of both countries does not just reflect the differences geographically, but could also show evidence of the uniform principle of water management beyond this within the civilizations. Simultaneously, it is also valuable to add new knowledge of historical water management comparatively among the civilizations and learn the lessons from history for sustainable water management. Accordingly and selectively, a comparison of urban water management and hydro-technologies developed through the long history of ancient Chinese and Greek civilizations was undertaken in this study.

In the early period of this within Chinese urban development, places near major rivers were strongly considered as the sites for building a city, especially rivers like the Yellow river and Yangtze river. Indeed, all the influential ancient cities in China were built close to major rivers. These rivers includes a series of the most influential ancient capital cities such as Anyang, Chang'an, Luoyang, Kaifeng, Nanjing, Hangzhou, Beijing, etc. For example, Anyang, the oldest capital city of China, was built along the banks of the old Heng Shui river. Chang'an, today's Xi'an city, was built close to eight rivers including the Wei, Jin, Lao, Feng, etc., and became the capital city for 1,700 years under thirteen dynasties. Kaifeng city was located between the Yellow river and Huai river. In addition, Nanjing city is located at the south riverside of the Yangzte river, etc. (Jin 2005). Being situated near rivers, the city had a convenient water supply and irrigation system, which later also made transportation convenient.

At the same time, the city also faced high flooding risk from the rivers. Accordingly, the ancient founders and governors of the cities always gave serious attention to combat urban flooding. Even later, many cities were built near the major canals, for example the Grand Canal Jinghan. However, the situation did not change (Tang *et al.* 2012.). It is also a fact that the early Chinese civilization was developed in the Yellow river basin. Accordingly, major cities were also developed in the Yellow river basin before the Nan-Bai dynasties (420–589 AD). After the Nan-Bai dynasties, the major cities along the Yangtze river were developed. This outnumbered the Yellow river basin hundreds of years later, alongside with the economic development of the basin (Dong 2004). Anyway, ancient Chinese, like the other early first human civilizations of Mesopotamia, Egypt, and the Indus river valley, were developed around the alluvial regions. Thus, this was located on the plains surrounding a river. As a result, water supply, wastewater, and stormwater management became an integral part of the first urban services (Ruddell, 2012).

The earliest event of water governance recorded in Chinese documents, as well as in popular folklore, was the story of Da Yu Governance of water which was led by the emperor of the Xia dynasty of China (*ca*. 2000 BC). However, in the 2nd millennium BC in China, food and water was in abundance without having a centralized government to organize large irrigation projects like in Mesopotamia or Egypt (Ruddell, 2012). A decentralized series of villages grew as the population increased, which led to the formation of the Shang dynasty (*ca.* 1766–1122 BC). He led the river governance successfully and therefore became the first king when early China was formed.

The Qin dynasty (*ca.* 221–206 BC) was the first unified imperial dynasty of China, which was formed after the conquest of six other states by the state of Qin. It was a short dynasty of 15 years, but before the Qin emperor founded the dynasty and during the dynasty, some great hydro-engineering were accomplished such as Zheng Guo Qi Aqueduct, Du Jiang Yan Barrages, Ling Qi Canal and so on. These projects profoundly influenced local development, including urban development, from their early stage up till now.

After the civil war that followed the end of the Oin dynasty in 207 BC, China was reunited under the rule of the Han dynasty (*ca.* 206 BC–220 AD) – one of the most flourishing dynasties of China. During that period, a technological revolution occured in China with the extended territory, establishment, and trade beyond the two major Chinese rivers. The establishment of the Han dynasty and its power and prosperity also brought a bloom in the period of urban development. Cities and towns were built in all the territory based on the orders of the central government. Accordingly, water supply, sanitation, and drainage systems were developed in the urban areas. Also, agricultural farms and irrigation systems occurred in a diverse environment. A remarkable achievement of urban hydrotechnology in the period shows that a model of urban water system was formed at the capital city, Chang'an, which had a significant influence on Chinese urban water system construction broadly in subsequent dynasties (Zheng 2015b). After the Han dynasty, China experienced a series of dynasties. Thus, more and more large cities were constructed as a result of the national blooming, population growth, trade development, and territorial development like major canals and the construction of irrigation systems. Along with these processes, the urban hydro-technologies were improved and developed to meet the demands of urban water supply, drainage, transportation, and industry. The main feature of the historical urban hydro-technologies development in China was dependent on rivers to manage the urban water. However, the purpose of a drinking water service was not included in the public urban water system construction until later in the 19th century. Before a tap water system was constructed in some large cities, people usually used wells or obtain water from the ditches nearby for drinking. Later in the 19th century, the daily use of tap water systems was getting popular in major cities. In most cities in the 1960s, it replaced wells and ditches as a daily water resource.

Chinese technological achievements and water culture appears to be autonomous. This means that there was no influence from abroad. Unlike other early civilizations (e.g. Indian and Mesopotamian), which had links with their western civilizations, Chinese early civilizations were characterized by cultural as well as political cohesion and continuity. This, however, was due at least, in part, to geography, bounded by deserts, steppes and oceans such as Siberia in the north, the great Himalayas in the west, and Pacific Ocean in the south.

On the other hand, the first human settlements in Greece, dating to the Aceramic Neolithic period, used cattle, sheep, goats, pigs, and dogs as well as domesticated cereals and legumes. The ancient Knossos in Crete was the site of one of these major Neolithic (later Minoan) sites. Consequently, Crete was the centre of Europe's first advanced civilization – the Minoan civilization (Mays *et al.* 2007). Archeological evidence suggests that a high civilization was developed in Crete and in the islands of the south Aegean sea (e.g. Santorini) during the Minoan era (*ca.* 3200–1100 BC). Furthermore, a systemic urban water system has been discovered in the Knossos palace town in the Minoan era. Among other evidence, this can be demonstrated by the advanced techniques used for water management during that period (Koutsoyiannis *et al.* 2008; Angelakis *et al.* 2012; Angelakis 2016, 2017).

Beginning *ca.* 1600 BC, the Mycenaean civilization took over on the mainland of Greece and the advanced Minoan water technologies were expanded to the Hellenic mainland by the Mycenaeans (Angelakis & Spyridakis 1996). Thereafter, in the Archaic and Classical periods of Hellenic civilizations, aqueducts, cisterns, and wells similar to the Minoan and Mycenaean originals were also constructed. It should be noticed that the development of water science and engineering in Greece appears not to be linear, but are often characterized by discontinuities and regressions. Greek technological achievements were not totally forgotten during the Greek Dark Ages, such as *ca.* 1100–650 BC. 'Bridges' from the past to the future are always present and, albeit often being invisible to those who cross them. A characteristic example of survival is provided by the several types of cisterns developed in Minoan and Mycenaean times which are still widely used in many anhydrous Hellenic islands. In addition, a continuous evolution of the engineering of cisterns whose 'bridges' have several historical periods has been clearly indicated (Angelakis *et al.* 2012).

However, the scientific and engineering progress of the age made possible the construction of more sophisticated structures in Classical Greece. During the succeeding Hellenistic period (*ca.* 323–67 BC), significant developments relevant to water supply and to a hygienic lifestyle were achieved in Crete and other islands in southeastern Greece. Hence, this period is based on Minoan knowledge (Angelakis & Spyridakis 1996). During this period, impressive accomplishments were achieved in hydraulics, such as in the construction and operation of aqueducts, cisterns, wells, harbours, water supply systems, baths, toilets, and sewerage and drainage systems. However, during the Hellenistic period, Greece did not stand in the cultural foreground during this time, nor did it play an influential role in international politics.

Later on during the Roman period (*ca.* 67 BC–330 AD), the Hellenistic hydro-technologies were expanded in size and in scope. Public buildings, often with fine mosaics, toilets, sewers, drains, and other hydraulic works, were established in a number of cities, especially in the capitals. In addition, public engineering works like buildings and roads and the first larger scale aqueducts and cisterns were constructed (e.g. the Gortys' aqueduct and cisterns in Aptera) (Davaras 1976). The Romans did not add much to the basic Hellenic knowledge, but enlarged the scale significantly. However, new technologies were invented, namely Roman concrete, the so-called '*opus caementitium*', which enabled the economic construction of even longer canals, huge water bridges, and long tunnels on soft rock (Fahlbusch 2010).

From 961 to 1204 AD, Greece was a part of the Byzantine Empire. Thus, very little progress in water hydro-technologies was achieved. Also, during the Ottoman period (1669–1898 AD), water was connected to religion, and the Ottomans maintained and operated water constructions that were mainly developed by Romans and Venetians (Angelakis *et al.* 2012).

By the end of the 19th and the beginning of the 20th centuries, the Greek state was established and the modern water technologies were being developed. This can also be seen in other parts of the world. They were based on past technologies as well as on deep wells, pumps, pipes, etc.

A number of scientific fields of water resources management were developed by both the ancient Chinese and Greeks through their long histories. The major focus of these fields include: hydrogeology, aqueducts and water impounds, water and wastewater mains, runoff management, agricultural irrigation, as well as the use of water for recreation purposes (Angelakis *et al.* 2005). In this review, a comparison of water management and hydro-technologies was developed through the long history of the ancient Chinese. Also, a study of Greek civilizations was undertaken. The major historical periods which are chronologically considered in this study are shown in Table 1 below.

THE PERIOD *CA.* 7000–1000 BC

Early prehistoric civilizations, including Chinese, bloomed in plain-areas closed to rivers. Here, water for agricultural development was readily available (e.g. Mesopotamians near the rivers Tigris and Euphrates in Asia, Egyptians near the Nile in Africa, and Indians near the Indus river).

According to archeological discoveries early Chinese urban history dates back 5,000 years. The earliest town ruins were discovered by the archeological digs in recent years in Liangsu Runis, Zhejaing Province, namely Liangsu culture. The earliest discovery of these ruins began in the 1930s. In recent years, the continuing excavation has found that there is a royal palace with a town existing in *ca*. 3000 BC, and the cultural relevance covered a large areas of today's east China, including Shanghai, Zhejiang,

Table 1 | The major historical periods considered in this study

Years (*ca.*)	**Period of China**	**Period of Greece**
7000–1000 BC	Prehistoric time Xia dynasty Shang dynasty Zhou dynasty	Prehistoric times Neolithic (*ca*. 7000–3200 BC) Bronze Age (*ca*. 3200–1100 BC) Mycenaean (*ca*. 1600–1100 BC) Dark Ages (*ca*. 1100–750 BC)
1000 BC–330 AD	The Spring-autumn Era (*ca*. 770–476 BC) Fighting-states Era (*ca*. 475–221 BC) Qin dynasty and Han dynasty (*ca*. 221 BC-220 AD)	Historical times Archaic (*ca*. 750–500 BC) Classical (*ca*. 500–336 BC) Hellenistic (*ca*. 330–67 BC) Roman (*ca*. 67 BC-330 AD)
330–1453AD	The Three States Era The Two Jin Era The South-North dynasties Sui dynasty Tang dynasty Song dynasty Yuan dynasty	Byzantine times (*ca*. 330–1538 AD) Ottoman period (*ca*. 1538–1821 AD) Present times (1821-present)

and Jiangsu provinces. According to the dig, the town, with a size of 3 million m^2, 1.50–1.70 km from east to west, and 1.80–1.90 km from south to north, is the largest town at the Neolithic period of China discovered so far. One of the most important discoveries in this site is that there is a complex urban hydro-system that was existing both inside and outside the town. It was constructed with ten dams and a long dyke to defend the flood and store water for urban supply. The main body of the dams was built by the interlining of grass and clay (Figure 1). Furthermore, the hydro system covering an area of about 100 km^2 is the earliest large scale hydro-engineering, and is also seen as the earliest urban hydro-engineering project discovered in China so far (Yubo *et al.* 2016). However, it is a fact that there were not many cities of such a scale existing at that time.

Before the first Chinese unified country was established in 221 BC by the Oin emperor, there were six local kingdoms located at the two major rivers basin and even more existed in earlier history. Accordingly, there were many cities that was also established inside the kingdoms. More especially, the capitals became the centre cities. In addition, the urban hydro-technologies also developed in this age. Due to the fact that most Chinese cities were established near river basins, the urban water supply was not a major problem. Nevertheless, urban drainage was a major problem due to the flood risk. Consequently, urban drainage technology was developed at the early urban historical age.

Figure 1 | Liangsu culture dam in which grass and clay are interlining.

According to archeological discoveries, dated back to 2300 BC, the urban drainage facility was built in the cities. The earliest drainage facility was discovered in the old town, Pingliangtai of Henan province. However, what was remarkable from the discovery was that the pottery used for the construction of the downcomer pipe inside the town (i.e. earthen pipelines for drainage) was found to be used in building an underground drainage system under the street (Henan Institute for Cultural Relic 1983). In *ca.* 10th–15th century BC in the Shan dynasty, urban development in Central China was developed into a golden age, and many major cities were formed near the Yellow river basin. Urban drainage was also improved accordingly. Archeological discoveries from Xihaocheng town, today's Yanshi city of Henan province, show that a systematical drainage system had been built inside the city. According to the archeological works, the city was around 1.9 million m^2. Also, there was an underground sewer with a length of 800 m which served as the main urban drainage sewer from the East Gate to the palace. Inside the palace, there were branch downcomers which formed a well-designed drainage system for draining rainwater and waste water. Hence, the underground sewer with a breath of 1.3 m and a height of 1.4 m directed water from the palace and town into most places (The Museum of Qi Kingdom Old city Site of Ling Zi District 1988). From about 1100–221 BC, many kingdoms were established in Central China close to the Yellow river basin and Yangtse river lower basin as a result of it. Thus, many cities were formed, and they brought a golden age to the history of China's cities. Along with urban development, urban drainage techniques also improved to a great extent. Archeological discovery shows that the urban drainage developed to a high level in Lingzi city, the capital of Qi kingdom in today's Zibo city of Shandong Province. During that time, Lingzi city was a major city with a population of 300,000 and 15 km^2 in size. A complex water supply and drainage system was built combined with river, drainage ditch, pipeline, and a moat. The city was built close to the river and was linked with a fosse. Also, three sewer networks were built in the city, gathering waste water and storm water into the fosse and again directing it to flow into the lower reach of the river. According to archeological digging, a major draining station was found under the west Rounding Town-Wall. The structure was made of stone with a length of 43 m and a breadth of 7 m. However, it leads water from the city and cross the wall into the river. The draining station has 15 outfalls which were distributed in three floors i.e. five outfalls per floor. Anyway, the drainage system of Lingzi city was the oldest and biggest one in ancient China from archeological discovery so far (Fan 1987). Also, it has been listed in China's National Important Relic Protection Site (Figure 2). However, the urban drainage technology reflected the high level of urban hydro-technology at that time.

By contrast, ancient Greeks avoided the establishment of their major urban centres close to rivers, lakes, or rich springs (Angelakis 2016). Observing carefully the locations of these centres, it should be noticed that most of them were established in the driest areas. The exact reason for this is not known, but it may be assumed that ancient Greeks considered a dry climate to be more convenient or healthier; thus, it was probably for protection from floods and water-related diseases (Koutsoyiannis *et al.* 2008; Koutsoyiannis 2012).

The major Hellenic civilizations chronologically shown in Table 1, which lasted for millennia, were established in uphill places or in small plains existing between mountainous areas under water scarcity (Yannopoulos *et al.* 2015). This was the case in both continental and insular ancient Greece (Zarkadoulas *et al.* 2012). Thus, wisdom in management appears to have been the solution to several water resource problems rather than technological development (Angelakis *et al.* 2012). The water demands of the first

Figure 2 | The Draining station of Lingzi city (with permission of Xiao Yun Zheng).

towns, built on hills, were met by springs. When the water needs increased due to agriculture, groundwater exploitation was expanded with the construction of wells (Voudouris 2012). It was known that the cultural and technological achievements in ancient Greece were mainly due to limited water resources, as stated by Plato (428–348 BC) that '*the need induces creativity*'.

The most significant characteristic of the Minoan civilization was their peaceful living in the environment and with neighbours. Although the Minoans dominated in the Mediterranean for almost two millennia, they were not directly or indirectly involved in any of the numerous wars and/or conflicts that occurred in the region (Angelakis 2016). For that reason, the Minoan era was named by A. Evans (Evans 1921–1935) as *Pax minoica* (or the Minoan peace), *a period when cities did not have walls*. It should be concluded that Minoans were living in harmony in the environment and they concentrated on technology, art, and culture. The Minoan technological achievements were passed on to Mycenaeans and then to Archaic and Classical Greeks. These technological developments that were unprecedented in the world's history are shown by the numerous paradigms on water resources technologies used and water, wastewater, and stormwater management by Angelakis (2016). In addition, few relevant paradigms follow.

Dams had been constructed in Greece since the Bronze age. In the Minoan era, the best known are those found in the valley of Choiromandres, located on the eastern end of Crete, with strong slope and direction from east to west (Angelakis 2017). In *ca.* 2nd millennium BC, Minoans attempted to regulate the flow of the stream through a system of two dams, in order to protect arable land from erosion after heavy rainfall, and also to irrigate their fields (Figure 3(a)). It seems that the construction started in the Palaio-palatial period (*ca*. 1900–1700 BC). The highest has a length of 27 m and a height of 3.10 m, whilst the thickness of the base is greater than that of the crest (Angelakis 2017). A channel in the eastern surface of the rock functioned probably as a spillway. Similar hydraulic structures are found on the island Pseira (Mochlos), located in the gulf of Mirabello in northeastern Crete (Betancourt 2012).

Later on, Mycenaeans extended this technology. During a flood (*ca*. 1250–1200 BC), a stream south of

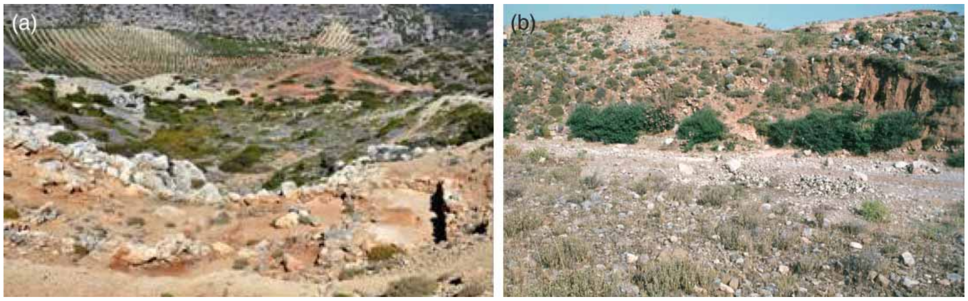

Figure 3 | Prehistoric Greek dams: (a) remnants of the upper-main dam Choiromandres and irrigated area (with permission A. N. Angelakis) and (b) remnants of the Tiryns dam; east face and detail of Cyclopean lining of east face (photos from http://devlab.cs.dartmouth.edu/history/bronze_age/).

Tiryns abandoned its bed and shifted to the north of Tiryns. To protect the lower town from future floods, the inhabitants of Tiryns installed an artificial river diversion consisting of a 10 m high and 300 m long dam and a 1.5 km long canal (Figure 3(b)). The dam is a huge earthen embankment lined with Cyclopean masonry across the earlier western streambed (Koutsoyiannis & Angelakis 2004).

One of the salient characteristics of the Minoan civilization was the architecture and operation of the hydraulic drainage and sewerage systems in palaces and other settlements. Of all the total infrastructure of the Minoan palace at Knossos, nothing was more remarkable than the complex but very functional sewers and drains, passing through the municipal facilities of the palace and its neighbouring districts. Evans (1921–1935) and MacDonald & Driessen (1988) described these hydraulic structures and proposed their original form with particular reference to their architecture and performance (Figure 4(a)). Another advanced Minoan drainage system seems to be found in the villa of Hagia Triada (Figure 4(b)). This system has been admired by several visitors, including the Italian writer, Mosso (1907), who visited the area in the early 20th century. During a heavy rain, he noticed that the pipes functioned perfectly and he recorded the incident saying: *I doubt if there is another case of a storm-water drainage system that works 4,000 years after its construction.* Also, the American Gray (1940) said: *you*

Figure 4 | Minoan sewerage and drainage systems: (a) the output of the central system of the Knossos palace and (b) part of the central system of the villa Hagia Triada (with permission of A. N. Angelakis).

can … doubt whether the modern sewerage and drainage systems will operate at even a thousand years. Therefore, the Minoan plumbers planned and constructed projects that functioned for centuries; unlike today, if a project operates well for 40–50 years, it is considered to be satisfactory (Angelakis 2017).

THE PERIOD *CA.* 1000 BC–330 AD

This period is an important period to shape the unified state and the urban water system, and also to drive the generation of the urban hydro-technologies in Chinese history. As mentioned above, the first unified country, Oin, was a short dynasty of 15 years, but the following dynasty, Han, was a powerful one for more than 400 years. However, there are many large cities that were formed during this dynasty. The most important urban hydraulic work was the urban water system design and construction of the capital Chang'an city which was considered as a model of urban water system that broadly influenced the urban water system construction in subsequent dynasties in China (Zheng 2015a).

According to archeological discovery, a complex water system was built in the city and it performed the functions of water supply, drainage, storage of water, and ship transportation. The city was found at the south side of Wei Shu river, but the water supply was from Jue Shui from the south of the city. Thus, it flows to the north into the town. Similarly, it also flows across the palaces and the city (this part is called Ming Ditch (9 km of length)), and then out of the town into Wei Shui river. The other branch of Jue Shui river also flows across parts of the town and then into the Wei Shui river. As a water system, series of hydraulic engineering were built to accomplish separate functions. For example, 10 large ponds were built for sluice, and the most famous one, which still exists today, is called Kunming Pond. This pond performs the functions of rainwater sluice in summer, and water storage and supply in winter. Outside the town, a fosse (length of 26 km) was built around the town. It was connected with the city river, Ming Ditch, and it also performs the function of a sluice of rainwater from the town. The water systems were connected to each other and to the water supply; rivers, ponds, drainage sluiceways, fosses, and drainage rivers.

Influenced by the urban water system construction of Chang'an city, the model of water system in an ancient city usually combines the following. (a) Water supply system: being a canal or river to introduce water into the city. (b) City's rivers: rivers or canals flowing inside the city as a water-cycle system with the functions of water supply and drainage. (c) Draining channel: a network of draining channels was built in palace and resident areas. However, some are underground whilst some are upper channels for draining waste water and rainwater into the city's rivers. (d) Ponds: built or naturally linked with the city's rivers and functions as a sluice and waterscape. (e) Fosse: a canal commonly built to surround the town which performs the function of defense and sluice, and the canal is linked with the city's water system. (f) Draining river: the river that passed the city or canal to direct water from the city into the lower basin of the river with the function of draining water from the town. By this systemic design, water was introduced from the nearby river to supply the city, and after cycling in the city through the water system, it then flows into the lower basin of the rivers. Also, the drained waster and rainwater from the town also flows into the lower basin of the river as well (Zheng 2015a). If rainstorm comes, the city's rivers, ponds, and round town-fosse perform the function of sluice for the storm water to reduce the risk of flooding.

Archeological discovery, in recent years, also shows that urban hydro-technology had been developed at a high level in Chang'an city. For example, in 2008, a major brick sewer was found in the old Chang'an town. This discovered sewer is 2 m in width and 40 m in length. Remarkable features of this sewer are: (a) it is the largest Han sewer discovered so far that shows the draining capacity was strongly considered; (b) brick was used as the building material and, basically, it was a very expensive material at that time but people considered its value for drainage; and (c) its arch structure could be considered as an advanced technique for sewer construction at that time because it was the first discovery. At the same time, compared with the later constructions, flagstone was more popularly used as the cover of the sewer in other Chinese cities (Figure 5).

Consequently, daily water supply for urban residents was not considered enough by public urban water system construction in ancient China when compared to some European countries like Greece, Italy, and so on. The

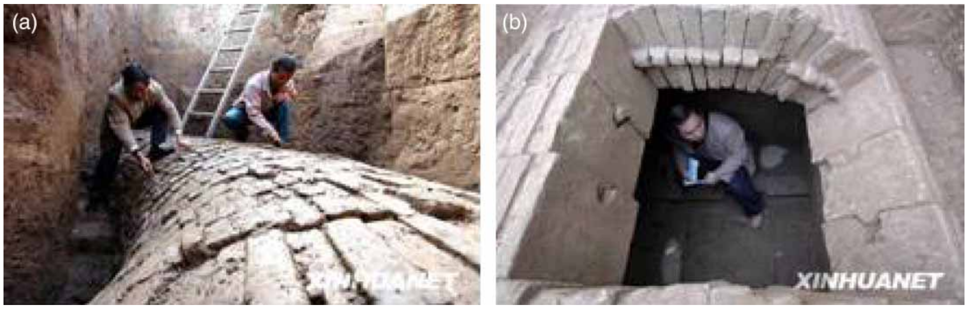

Figure 5 | The brick structured sewer of Han dynasty: (a) the brick structured sewer was in the dig work and (b) the large arch sewer was discovered for the first time (Feng 2008).

water system is usually considered as the urban infrastructure, but the final water used facility was neglected. Accordingly, wells were used popularly as the final water structures in residential areas. Before the unified Oin dynasty was established, there were many cities existing inside the kingdoms. Also, archeological discovery shows that wells were popularly used for daily water supply in the cities. For example, wells were popularly used for daily water supply in Yun city (*ca*. 5th century–279 BC), the capital of Chu Kingdom located on the north bank of the Yangtze river. Excavation of the ruins has discovered more than 400 wells inside the city. Among them, there are 256 that were found along a zone of 1000 m in length which could be considered as a main residential area (Dong 2004).

The structural feature of the well was developed in different ages. According to archaeological discovery, the early well (around 3000 BC) was built with wood, and the form was usually square. In the Fighting-States period (475–221 BC), the well walls were built with earthenware since it was a very popular structural material at that age. An earthenware well of early Han dynasty, that was discovered in Yeng county, Hebai Province, is shown in Figure 8(a). It is evidence that earthenware was used for the building of wells at that time. According to the report, about 40 wells were discovered in the same ruins. Each well was 5–7 m in depth and 1.3 m diameter (Figure 6). In Han dynasty (202 BC–220 AD) and subsequent dynasties, the wells which were built with brick became more popular, and were stronger and diversiform (Chong 1991). But in Han dynasty, wells were still built with wood, earthenware, and brick. Sometimes, the wells were a mixed construction built with wood and earthenware (Zheng 2014).

In Greece, during Classical times, the introduction of the Hippodamian system in city planning is a significant novelty, which during the Hellenistic period and up to modern times, influenced urban water, wastewater, and rainwater systems markedly (Kollyropoulos *et al.* 2017). Kassope, Miletus, and Olynthus are considered as very good examples of ancient cities built on a rectilinear street grid of a Hippodamian plan in Greece (Hippodamus of Miletus,

Figure 6 | Chinese wells: (a) built with earthenware in early Han dynasty and (b) an earthen model of a well in Han dynasty.

498–408 BC). Their drainage and sewerage systems were very advanced and had a high performance (Tuttahs 1998; Zarkadoulas *et al.* 2012).

In addition to the town, the theatres in ancient Greece have impressive drainage systems. For example in the Aegean island Delos the theatre had a perimetrical open channel, built from the same material as the theatre, which collected the rainwater and drained it to a large vaulted cistern, located 200 m west and downwards of the theatre (Kollyropoulos *et al.* 2015). The storage water was one of the major water source of the waterless island, mainly for the theatre neighbourhood.

In Classical and mainly in Hellenistic times, the following were also established: admirable balances between structural and nonstructural (institutional) measures; large-scale (e.g. the Peisistratean aqueduct) and small scale (wells and cisterns) projects; and the interests of the public for large-scale works and the private for small-scale works sectors (Koutsoyiannis *et al.* 2008). In Athens for example, there were two main streams, Ilisos and Kephisos. Also, the small springs in the area could not meet the demand of the city and the water supply was based on wells, both public and private (Figure 7). Over 400 wells were found with a great variation in depth, which ranged from 2.5 to 37 m since the early Classical period (Angelakis 2016). The well known as the 'Peisistratean aqueduct' was constructed during the Peisistratus tyranny (546–527 BC), which was considered as the most important public hydraulic work at that time. At the same time, the famous Eypalinean *όρυγμα* (tunnel) was constructed in the Aegean island Samos (Voudouris *et al.* 2016).

After democracy was established in Athens (*ca.* 510 BC), wells were gradually complemented or replaced by cisterns. The construction of cisterns was a known practice since earlier times; for instance, several of them from the 6th century BC have been found inside the Acropolis wall to the left of the Propylaea (Koutsoyiannis *et al.* 2008). Water cisterns were constructed in several places in Greece during the Hellenistic times.

Apart from the applied technologies for water supply and drainage and sewerage systems in urban centres, the ancient Greeks developed legislative frameworks for water management. The first known regulations were introduced by Solon, the Athenian statesman and poet, who was elected

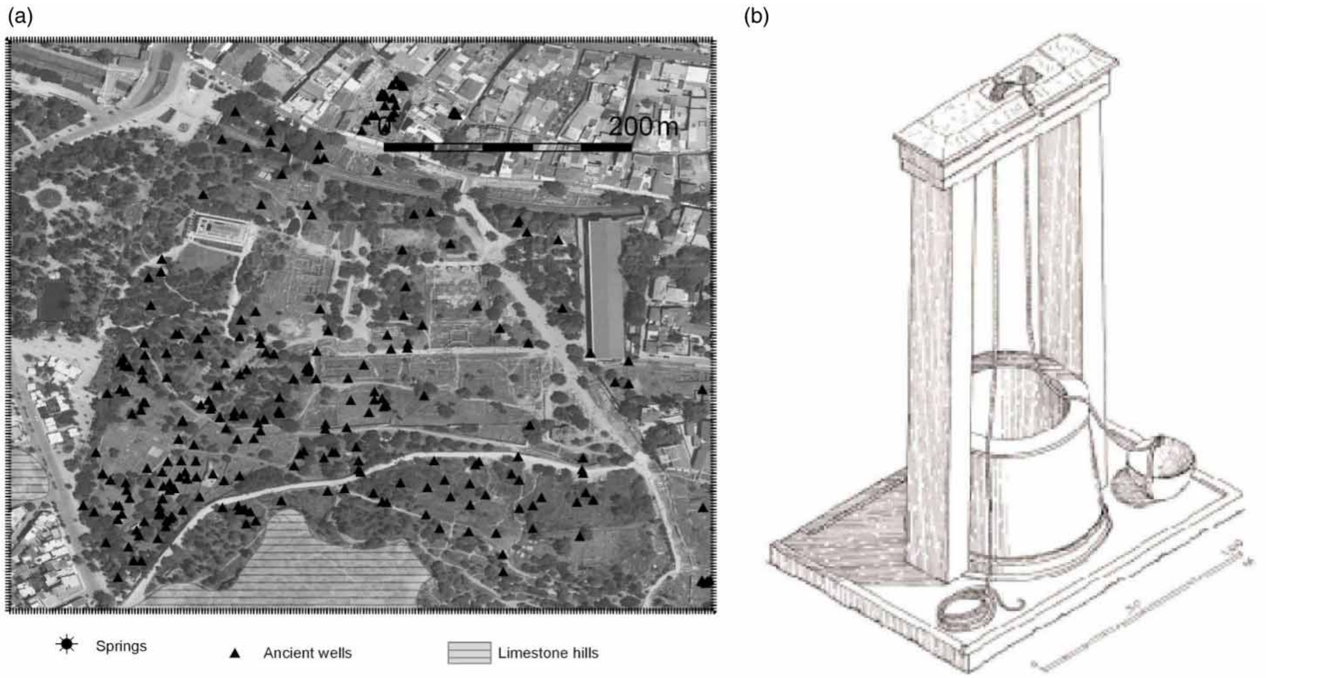

Figure 7 | Classical period wells: (a) distribution of ancient wells around the Athenian Agora (data from the American School of Classical Studies at Athens) (Angelakis & Voudouris 2014) and (b) sketch of typical well (Camp 2002).

archon in 594 BC and shaped a legal system by which he reformed the economy and politics of Athens (Koutsoyiannis & Patrikiou 2013; Angelakis 2016). He established, among others, a legal system to regulate and encourage the use of wells, which is described later on by Plutarch (45–120 AD), from whom we learn:

> '*Since the area is not sufficiently supplied with water, either from continuous flow rivers, or lakes or rich springs, but most people used artificial wells, Solon regulations considered; wherever there was a public well within 710 m, this was to be used; where it was farther away, one could dig one's own. But if having dug to a depth of 18.30 m, one did not find water, one was permitted to fill a five-gallon pitcher (20 L) twice a day from one's neighbour's well. It is pointed out that, after passing his legislation, Solon went into voluntary exile to avoid being pressured into amending his legislation*' (Plutarch, Solon, 23).

In the implementation of public projects in ancient Greece, it was a common practice to announce the project specifications by writing on marble steles erected in public sites. This was done so that everyone would have known all project details and, simultaneously, it was difficult to breach the contract project. (a) An interesting paradigm is the Contract for the construction of flood drain at the sanctuary of Amphiareion, dedicated in the late 5th century BC to the hero Amphiaraos. It is situated in the hills of Oropos, and is located 37 km northeastern of Athens. Hence, the contract was dated 335–322 BC. (b) Another interesting paradigm is the contract for draining and exploitation of the lake Ptechae in Eretria in central Greece (probably identified with the Dystos lake in southern Euboea). Other regulations protected surface waters from pollution (MacDowell 1978). An epigraph of *ca.* 440 BC contains the 'law for tanners', who are enforced not to dispose their wastes into the Ilissos river (Pappas 1999).

As the urban public systems grew and aqueducts transferred water to public fountains, private installations like wells and cisterns tended to be abandoned. As the latter would be necessary in times of war because the public water system would be exposed, the owners were forced by regulation to maintain the wells at a good condition and ready to use (Korres 2000).

The entire regulatory and management system of water in Athens must have worked exceptionally well and approached what today we call sustainable water management. For example, modern water resource policymakers and hydraulic engineers have, in recent international conferences, emphasized the nonstructural measures in urban water management and the importance of small-scale structural measures like domestic cisterns. Such cisterns have two advantages: they reduce stormwater quantities and potential flood risks, and increase water availability by providing a source of water for use (like watering of gardens) (Angelakis 2017).

THE PERIOD *CA.* 330–1453 AD

After the Han dynasty, there was a series of dynasties which existed in Chinese history until the Oin dynasty ended in 1912. Unfortunately, many large cities, especially the capitals, were destroyed by civil war during the replacement of the dynasties. However, on the other hand, China also experienced some powerful dynasties and blooming periods that brought the opportunities of rebuilding their cities, for example, the new Chang'an city during the Tang dynasty; Kaifeng city during the Song dynasty; and Beijing city during the Yuang dynasty, etc. In the Tang dynasty, one of the most powerful and prosperous Chinese dynasties, the Jing-Hang Canal network was constructed finally. It also brought rapid urban development along the canal. Also, many influential cities were developed along the canal at or after this period, for example, Hangzhou city, Suzhou city, Yangzhou city, etc. The main feature of the urban water management and the hydro-technologies development after Han dynasty is the continuous management of the river for urban water supply, drainage, flood control, ship transportation, industrial demand, recreation, and so on. This is based on the fact that most Chinese cities were built close to rivers or canals. This situation changed after the 1960s.

Shaoxi City is a paradigm. Being located at the west of Zhejaing Province, Shaoxi city is a very famous city not just because of its long and important history or local culture, but it also has a typical urban water system. The history of Shaoxi city dates back to 2,500 years ago. From the original history of the city, the city was found with abundant water. There are 43 rivers from the Kuai Ji Mountains to the north flat, which bring abundant water to this region. Consequently, the city was built with a convenient water resource, but the urban water system was an artificial one. In Tang dynasty (618–907 AD), the Zhe Dong canal was built to link Shaoxin town. It brought more water resources to the city. In Song dynasty (960–1279 AD), the water system of the city was formed with supply rivers, urban rivers, moats, lakes, and rivers. What was remarkable was that many urban rivers were built inside the town. Also, after a river has been built, the streets and houses were built close to the riverbanks, therefore forming a water net inside the town. In the Qing dynasty (1636–1912 AD), a complete water system was combined with 33 rivers inside the town, 60 km of total length, two moats (inside and outside town), and 27 lakes and ponds. Thus, they were all linked to each other as well as to the water systems outside the town. For instance, eight out of nine town-wall gates were mainly for river crossing, as there was linkage of the rivers with Zhe Dong canal, lake Jian, and other rivers. Therefore, the water system perfectly performs the function of water supply, cycle, use, drainage, and transportation; thus, it also sustained the local social life (Qiu 2012).

As well as hydro-technologies, hydroengineering and especially dam related technologies were also reflected in institutional design and management. Tuo Shan Yuan dam is a key hydro work for Ningbo city which was built in 884. Located at Yun Jiang river upper basin, it was built for the purpose of seasonal water regulation, urban water supply, drainage, and against seawater reversion; however, it performs a function with other three floodgates even today and has played a key role in the urban history of Ningbo city (Yuang 1984). The dam with a length of 134.4 m and width 4.8 m was built with flagstones (Figure 8(a)). At the same time, another stone dam in Ningbo city was built to regulate the water of Qian Dong Lake for urban water supply and irrigation. It is used to store water during the dry season and allows water across it for drainage during rainy season. In addition, it is still functioning until this day (Figure 8(b)).

Inside Ningbo city, ancient people used floodgates in the urban water system to regulate the water level to store water and for drainage. Stone tablets were built to measure the water level in the urban water system so as to regulate the water level by the floodgates. It was built from 1253–1258 (Song dynasty) and was continually rebuilt in subsequent dynasties. These reflected advanced urban hydro-techniques at that time.

By contrast, the Athenian example described earlier manifests admirable balances between structural and non-structural (institutional) measures; large-scale and small scale projects; and interests of the public sector for large-scale works and private sector for small-scale works (Koutsoyiannis *et al.* 2008). Today, similar solutions are often sought for both in developed and developing countries, as neither the public nor the private sector alone can provide sustainable solutions to water supply (Koutsoyiannis *et al.* 2008). In modern Athens, the responsibility for the management of the water supply system was initially assigned to the municipality and the central government; then (in the 1920s) it passed to a private company, which about 50 years later became a public organization that was re-privatized 6 years ago. However, these forward and backward

Figure 8 | Chinese dams: (a) the Tuo Shan Yuan dam and (b) the Qian Dong Lake dam (with permission of Xiao Yun Zheng).

changes clearly indicate that such a balance between private and public interests has not been established to date (Koutsoyiannis *et al.* 2008).

Also, in the region of Thessaloniki in the North Country, the same more or less water supply management regime exists. For the rest of the country, the responsibility of water supply management has been undertaken by Municipal Enterprises for Water Supply and Sewage due to a mixed pattern among private and public sectors.

CONCLUSION

China and Greece are two old countries in the east and the west each with a very long history, and with a long distance between them. However, there were common philosophical grounds in both ancient China and ancient Greece, such as Confucius and Socrates with regard to the core of ethics, Meng Zi and Plato with regard to the basic principles of justice, and Xun Zi and Aristotle in terms of philosophical realism. We do not know why and how that happened. But the fact remains that it happened. Archaeologists and historians believe that the designs for the *ca*. 8000 life-like clay warriors discovered near the tomb of China's most famous Emperor could have been influenced by ancient Greek sculptures, which arrived in China more than 1,500 years before the travels of Marco Polo (Jarus 2013; Kennedy 2016). Whether this same possibility holds for water resource design achievements need further confirmation. In conclusion, there are many differences as well as similarities and valuable lessons to learn on water resources management, especially those in urban areas, in both countries. The first major similarities are as follows:

(a) Water deeply embedded the civilizations of both countries and became the dynamic fact of their civilizations' development. A unique historical phenomenon was that during a similar era, around *ca*. 800–200 BC, there were many great philosophers in China and Greece who have influenced not just in both countries, but also east and west societies for more than two thousand years. Many of them deeply thought about the natural features of water and were inspired by water to structure their philosophy. For example, Guanzi (723–645 BC), Laozi (571–471 BC), Confucius (551–479 BC), and Xunzi (313–238 BC) in China were inspired by water to form their philosophy and thought about the universal origination and its structure, human life, morality, social management, state governance, urban construction, etc. (Jin 2003). At the same time, Thales of Miletos (624–546 BC), Herodotus (484–425 BC), Plato (428–348 BC), Aristotle (384–322 BC), Theophrastus (371–287 BC), and others in Greece thought and discussed the role of water in the construction of the nature and the origination of water, rivers, lakes, and water cycle, rainfall, Nile flooding, water law, etc. They began hydrology as a science as well as believing that the natural principle of water could be used in building their philosophy without involving the divine (Biswas 1970). Actually, hydro-techniques started in China and Greece as early as *ca.* 2000 BC, but in around 600 BC. Greek philosophers developed the scientific views of natural phenomena for the first time ever with water as one of the most important matters (Koutsoyiannis & Angelakis 2003). This phenomenum was in coincidence with Chinese philosophers who developed water from native use into philosophic and scientific views, putting cultural and social attributes into water, and bringing expansive influences to the world. This phenomena was unique in the human history of the ancient Chinese and Greek civilizations which also included the principles of hydro-technologies.

(b) Both countries were cradles of many hydro-technologies which included urban hydro-technologies, such as wells, dams, fountains, aqueducts, cisterns, water sanitation, etc. Many of the technologies were generated from two ancient countries locally, but were later separated, improved, and developed into larger geologic areas. For example, the Etruscan civilization included water management that was strangely influenced by Greece, flourished in the Roman Era, and remained unsurpassed until the end of the 18th century AD (Dragoni & Cambi 2015).

(c) Systematic design and construction of the urban hydrosystem were the major similarities of both countries in ancient times. The case of the Knossos ruins on Crete discovered a systematical urban hydro-construction that was combined with aqueduct, water distribution, drainage, cistern, sanitation, etc. In the case of China, the systematical urban water system was built as early as the construction in large scale in Asia. These hydro-technologies were generated and applied locally in both countries, but it formed many principles for the later ages.

Thus, both countries had many similarities of the urban hydro-technologies in their ancient civilizations. However, according to the geographic difference of both countries, there were many differences among both as well. Some of them are as shown below:

(a) Earlier Chinese civilizations (as others, e.g. Mesopotamian, Egyptian, and Indus valley) bloomed in large river valleys, which had water in abundance. However, Greece does not have large rivers, and the early civilizations were established in small plains located between mountains. Therefore, the water management was in line with these features, for example, spring water and rainwater for water supply was a priority.

(b) Large-scale and systemic urban hydro-technologies were developed in Greece earlier than China on account of the urban history of both countries. Basically, China is an agricultural based country. Its early urban development started at around 400 BC in central areas, but for the case of Greece, the systemic urban hydro-construction began in the Minoan age around 1900 BC on the island of Crete.

(c) According to the differences in geographical characteristics, urban Chinese development was strongly dependent on rivers. Since early times, the management of the rivers for urban water supply, cycling, and drainage were the main water institutional tasks. Also, urban hydro-technologies were developed in line with those conditions. Such technologies were mainly dam, floodgate techniques, and irrigation practices. On the other hand, Greeks usually lived in dry areas under very low water availability which developed cisterns for the storage of both rain and spring water, aqueduct for transporting spring water to the urban areas, and as well as the use of groundwater. In addition, they developed urban water distribution and wastewater and stormwater management systems since prehistoric times.

(d) Ancient Chinese urban water management was strongly focused on the water systemic design which logically depends on a river to construct its urban hydro-network. Thus, Greek ancient urban water management was more technological in the urban hydro facilities. Comparatively, the urban hydro-technologies in Greece were developed earlier than those of the Chinese.

(e) Usually, Chinese ancient urban water systems were built as a part of urban infrastructure. However, it neglected public water service. Technologies such as water supply by canals, urban river, and drainage facilities were built inside a city. In most cases, there is no water distribution system. River water was used for washing and irrigation. Usually, well water was used for potable use.

(f) In both civilizations, the large-scale urban hydro-works was usually operated by the governments, but the small-scale works were operated by the residents. The similar thing at this point is the well. Wells were used popularly in ancient cities of both counties as the final facility of groundwater use. This therefore brought together the urban hydro-technology similarity to both. In addition, water harvesting was a common practice in Greece since very early times, which was in use in China since the 3rd millennium BC (Oweis *et al.* 2004).

Finally, it is now well documented that modern day water technological principles have a foundation dating back three to four thousand years. These achievements include technologies such as dams, wells, cisterns, aqueducts, water distribution systems and sewerage, and drainage facilities. In both countries, these technologies have played an important role in the process of civilization growth and in national development. Also, it shows that the use of traditional knowledge may play a major role in solving some of the present day and future water resources sustainability issues, especially in developing parts of the world. Today, a lot of urban water related problems (e.g. rainstorm flood, water shortage, pollution, and city drainage) are strongly related to changes in and/or distraction of the historical urban water systems (Zheng 2015b).

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