Water and wastewater management technologies through the centuries

G. De Feo, P. Laureano, R. Drusiani and A. N. Angelakis

ABSTRACT

The aim of this paper is to propose a journey through the history of water and wastewater management technologies in the ancient civilizations, a sort of Appian Way ("*Via Appia*", the "*regina longarum viarum*") through the Centuries. Moreover, this paper is a sort of short summary of papers presented in the first two IWA Specialty Conferences on Water and Wastewater Technologies in Ancient Civilizations with particular emphasis on the later one. The main topics considered are: aqueducts and tunnels, cisterns and reservoirs, water distributions systems, fountains, toilets and other purgatory structures, drainage and sewerage systems, irrigation systems and, finally, qanats and other similar systems. Upon completing the journey, we have arrived at the conclusion that the meaning of sustainability in modern times should be revaluated in light of ancient hydraulic water and wastewater works and management practices.

Key words | ancient civilizations, aqueducts, cisterns, drainage, fountains, irrigation, qanats, reservoirs, sewerage, toilets

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INTRODUCTION

Thales from Miletus (636–546 B.C.) stated that "*Hydor (water) is the beginning of everything*". As a matter of fact, our life begins in water and water is a source of life. People have always had to deal with the need of having enough water for their uses and subsequently manage appropriately the produced wastewater. The availability of high quality water as well as a safe management of the produced wastewater has been a prerequisite for every urban development in every part of the world. Water filtering techniques and channels for conveying wastewater to fields for fertilization purposes have been used in Syria and Palestine since the earliest Neolithic societies spread East and West of this area with the propagation of agricultural villages and sedentarism.

In time these methods became increasingly more elaborate. In the 4th millennium B.C. the so-called trenched villages were encircled within drainage ditches which also made water available both for drinking and for irrigation.

In the trenched village of Murgia Timone, near Matera in Southern Italy, there are water collecting cisterns connected between them to form a filtering system and making rainwater drinkable (Laureno 2006). In China, the village of Banpo, near Xian, dating back to 4500 B.C. has ditches interrupted by stone walls for filtering and purifying water. In the Bronze Age, the Edomite civilization, later to become Nabataean, spreading from Petra in Jordan to the Negev and all over the Arabian Desert, contrived water sterilization methods made of layers of stones, sand and charcoal.

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In 3rd millennium, with the growth of the hydraulic civilizations along the Nile in Egypt, the Tigris and Euphrates in Mesopotamia, the Oxus (Amu Darja) and Axartes (Syr Darja) in Central Asia, the Indus in the Indian subcontinent and the Yangtse in China, complex urban centres emerge provided with aqueducts, water drainage and sanitation methods. The cities of Harappa and Mohenjo Daro, belonging to the Indus civilization, had houses provided with running water and sanitation systems. Near the Tchoga Zanbil Ziggurat, in Iran, the Elamite civilization created, in the 2nd millennium BC a remarkable water filtering system made of baked bricks (Khajeh 2006). Such practices spread eastward, along the string of oases which will later become known as the Silk Road, with its numerous branches leading up to Lijiang, in China, at the foothills of Tibet, and westward to the Mediterranean where, such as in the Sassi of Matera, the scarcity of surface water made people devise methods of rainwater collecting and management.

Water has long been transported from the source to its final destination by means of an aqueduct. The achievements in water and wastewater management practices, during the Minoan era, carried out to support the hygienic and the functional requirements of palaces and cities were so advanced that they could only be compared to the modern urban water systems that were developed in Europe and North America in the second half of the 19th century (Angelakis & Spyridakis 1996). It should be noted that hydraulic technologies in Minoan era are not merely limited to urban water and wastewater systems. These technologies, even though they do not give a complete picture of potable water, wastewater and stormwater technologies in ancient Greece, illustrate that they have been used in the prehistoric world for about 4,500 years. These advanced technologies began in Minoan Crete, subsequently expanded to Mycenaean and then to Ancient and Classical Greece as well as Rome. In light of the historical and archaeological proof, present day progress in urban water and wastewater technologies as well as in comfortable and hygienic living is not as significant as we tend to believe (Koutsoyiannis *et al.* 2008). These techniques constitute an extraordinary heritage of appropriate solutions, useful today for saving water resources (Laureano 2000).

In particular, the Romans were masters in realizing aqueducts and tunnels because they had great teachers: the Minoans, Greeks and Etruscans. The need to store water for different uses has determined the construction of cisterns and reservoirs. The water stored in a reservoir or transported by an aqueduct has to be subsequently distributed through the end users by means of a network of piping. Water supply systems have changed through the centuries due to the material used for pipe construction. A visible manifestation of the water supply systems is offered by fountains, and in particular by those located in streets and squares. They were not only a device to furnish water but also a form of art. Following the natural human physiological cycle, toilets are required as a call of nature. They have a long history with the first proof of a flushed toilet in Europe coming from the Bronze Age in Minoan Crete in the second millennium B.C. In addition, the ability to drain runoff of rainwater and control and dispose of wastewater had to be developed in order to transport and bring freshwater into cities. Since the beginning, people had to artificially supply water to supplement natural precipitation for the purpose of agricultural production. Irrigation still remains the main final usage of water. Qanats (and similar systems) are the last leg of our journey. First developed in the area spanning from Kurdistan and Baluchistan, as the outcome of an experience in digging surface channels and wells, and to the development of mining techniques.

In this paper, a historical journey of water and wastewater management technologies in the ancient civilizations, a sort of Appian Way ("*Via Appia*", the "*regina longarum viarum*") through the centuries is undertaken. Moreover, this paper is a sort of short summary of the paper presented in the first two IWA Specialty Conferences on Water and Wastewater Technologies in Ancient Civilizations. Emphasis is given to ancient technologies such as aqueducts, cisterns, qanats, and reservoirs, water supply distribution systems, fountains, drainage and sewerage systems, toilets, irrigation systems.

AQUEDUCTS AND TUNNELS

Aqueducts are man-made conduits for carrying water across hollows or valleys and have been used since the Bronze Age. In Minoan Crete, the technology of transporting water to "palaces", cities and villages by aqueducts was highly developed due to the mountainous terrain. Water was transported through the aqueducts by closed or opened pipes (terracotta) and/or opened or covered channels of various dimensions and sections. The mains of these aqueducts were in Gournia, Karfi, Knossos (Mavrokolympos), Malia, Mochlos, Minoa, and Tylissos. These technologies were further developed during the Hellenistic and Roman periods in Crete, and were transferred to continental Greece as well as other Mediterranean and nearby East countries (Angelakis *et al.* 2007; Angelakis & Spyridakis 2010).

Roman aqueducts subsequently became very famous all over the world, with Rome's water supply system being considered one of the marvels of the ancient world (Hodge 2002; De Feo & Napoli 2007; De Feo *et al.* 2009*a*). In fact, the Romans were "urban people" and consumed enormous quantities of drinking water in order to supply baths, public and decorative fountains, residences, garden irrigation, flour mills, aquatic shows and swimming pools (Hodge 2002; Tolle-Kastenbein 2005; De Feo & Napoli 2007; Mavromati & Chryssaidis 2007; De Feo *et al.* 2009*a*). However, the Roman aqueducts were not built to provide drinking water, nor promote hygiene, but either to supply the thermae and baths or for military purposes (Hodge 2002; De Feo & Napoli 2007; De Feo *et al.* 2009*a*). The description of the ancient Roman water supply system is contained in some recommendations of the Latin writers: *Vitruvius Pollio* (*De Architectura*, book VIII), Plinio the Elder (*Naturalis Historia*, book XXXVI), and Frontinus (*De Aquaeductu Urbis Romae*). The Romans were not the first to construct aqueducts. In fact, it is well known that the Greeks were the first to realize an aqueduct during the classical period (De Feo & Napoli 2007). One of the most famous aqueducts in ancient Greece is the tunnel of Eupalinos for the water supply of Samos (Koustoyiannis *et al.* 2008).

Roman hydraulic engineering borrowed from the experiences and techniques of the Etruscans, and in part from the Greeks. However, the size of the works as well as the technical-organizational features of distribution started with them. The common Greek practice was based on underground conduits, following courses determined by terrain features (Martini & Drusiani 2009). The Etruscan civilization flourished in central Italy from the VIII century B.C. onwards. The Etruscan talent for water and land management is highlighted by the existence of an imposing number of works (tunnels and canals) spread over their territories of Latium and, to a lesser amount, of the other Etruscan areas (Bersani *et al.* 2010).

The construction of an ancient Roman aqueduct was not different from the modern practice, with several modern technologies coming from Roman engineering. The building of an aqueduct started with the search for a spring. Water was collected after permeating through vaults and walls of draining channels and settled. From the spring, water flowed into an open channel flow and air was present over the water surface (Monteleone *et al.* 2007). The water in the aqueducts descended gently through concrete channels. During the route, there were multi-tired viaducts, inverted siphons and tunnels to exceed valleys or steep points. At the end of its course, the channel entered into a so called "*Piscina Limaria*", a sedimentation tank to settle particulate impurities. Then, the channel flowed into a partitioning tank called "*Castellum Divisorium*" where there were some walls and weirs to regulate the water flowing into the urban pressure pipes (De Feo & Napoli 2007; Monteleone *et al.* 2007).

There are eleven reliable records describing the Imperial age Roman aqueducts, with a total flow rate of 1.17 Mm^3/d and a total length of more than 500 km delivering water that was of excellent quality (Martini & Drusiani 2009). The total discharge of the ancient aqueducts in Rome (excluding Aqua Traiana and Aqua Alexandriana, whose data are missing) was 24,360 *quinariae*, corresponding to 1.01 Mm^3/d. The population of Rome at the end of the 1st century A.D. was about 500,000 inhabitants. Consequently, a mean water use of 1,550 L/d inh. has been reported (De Feo *et al.* 2010*a*).

In 2003, the Italian Speleological Society (SSI) started a project, dedicated entirely to the study and the exploration of ancient underground aqueducts, called "The map of Ancient Aqueducts of Italy". Water was transported to 19 regions of Italy through 123 ancient aqueducts. Latium hosts the majority of aqueducts, counting 40 hydraulic works, followed by Marche (13), Apulia and Campania (11), Abruzzo (9), and Piedmont (7) (Parise 2009).

The Campania Region, in Southern Italy, in particular, hosts two interesting infrastructures of the Augustan period. The first one is the Augustan Aqueduct Serino-Naples-Miseno, which is not well known due to there being no remains of spectacular bridges, but it was a masterpiece of engineering and one of the largest aqueduct systems in the whole Roman Empire. The Serino aqueduct was constructed during the Augustus period of the Roman Empire, probably between 33 and 12 B.C. when Marcus Vipsanius Agrippa was curator aquarum in Rome, principally in order to refurnish the Roman fleet of Misenum and secondarily to supply water for the increasing demand of the important commercial harbour of Puteoli as well as drinking water for big cities such as Cumae and Neapolis. The main channel of the Serino aqueduct was approximately 96 km long, and had 7 main branches to towns along its trace such as Nola, Pompeii, Acerra, Herculaneum, Atella, Pausillipon, Nisida, Puteoli, Cumae and Baiae. Since the total length of all the branches was approximately 49 km, the Serino aqueduct complex had a length of about 145 km and it should therefore be considered the longest aqueduct system in the Roman world (De Feo & Napoli 2007; De Feo *et al.* 2010*a*). The other important infrastructure is the aqueduct from Serino to Beneventum. This aqueduct (locally known as "*Samnite*") was neglected by Latin authors and local historians due to the proximity of the more famous Serino aqueduct. The main channel of the aqueduct Serino–Beneventum in its route was approximately 35 km long and had two small branches. A well preserved stretch of the aqueduct was discovered in Benevento within the "Rocca dei Rettori" which is the old Castellum Aquae (De Feo *et al.* 2009*a*).

The tunnel of 19.7 km under the Bologna hills is also very interesting. By the year 30 B.C., Bononia or Bologna had become so important that it needed to provide its inhabitants with infrastructures and services such as theatres, fountains, and baths, typical features of the capital, Rome. Augustus promoted the construction of important public works, such as the aqueduct, which was thus given the name of the Augustan aqueduct. The technique used to construct the tunnel was based on the well-known system of intermediate wells and teams of labourers advancing from opposite directions along the proposed tunnel (Drusiani *et al.* 2010).

CISTERNS AND RESERVOIRS

Cisterns were usually constructed in order to store rain water for domestic use (private houses), with a volume in the order of dozens of cubic metres (Tolle-Kastenbein 2005). While, reservoirs were realized in order to store flowing water with a volume in the order of thousands of cubic meters (Tolle-Kastenbein 2005; De Feo *et al.* 2010*a*).

In ancient Crete, the technology of surface and rain water storage in cisterns for water supply was highly developed and was used up to modern times. One of the earliest Minoan cisterns was found in the canter of a prepalatial house complex at Chamaizi dating back to the turn of the 2nd millennium B.C. There were cisterns on the high grounds above the palace in Minoan Malia, in a site lying in a narrow plain between the mountains and the sea. At the famous Phaistos palace, cisterns depended on precipitation collected from rooftops and yards. A supplementary system of water supply was needed to satisfy the needs of water supply, especially in those areas where agriculture was intensive. The cisterns were associated to small canals collecting spring water and/or rainfall runoff from catchment areas. The use of cisterns preceded canals or aqueducts in supplying the palace and the surrounding community with water (Angelakis & Spyridakis 2010).

Reservoirs constructed by the ancient Romans were set low in the ground, or actually underground, and roofed over, by means of concrete vaulting. The roofing vaults were supported by rows of columns, piers, or wall pierced with doors to allow the water to circulate. In some cases, the floor was slightly concave with a drain in the middle, to permit cleaning (Hodge 2002; De Feo *et al.* 2010*a*). The reservoirs had two functions: a reservoir could be a reserve for use when the aqueduct ran low, by adding in a little from the tank every day to supplement supplies until the aqueduct discharge picked up again. When the daily consumption exceeded what the aqueduct could bring in, at least in the hours of daylight, the reservoir was topped up every night to meet the next day's demands (Hodge 2002; De Feo *et al.* 2010*a*).

In Figure 1, there are three spectacular examples of Roman reservoir. The first is the biggest Roman reservoir: the Yerebatan Saray in Istanbul with a maximum

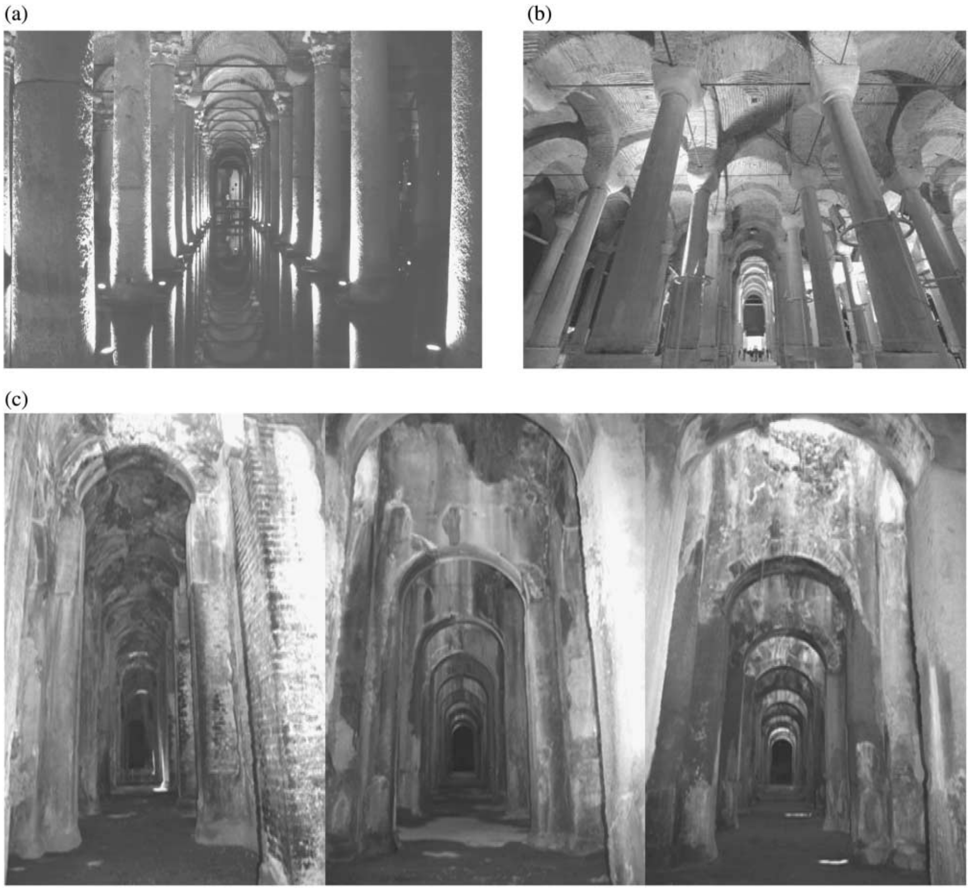

Figure 1 | Some examples of Roman reservoirs: (a) the Yerebatan Saray in Istanbul; (b) the Binbirdirek reservoir in Istanbul; (c) The Piscina Mirabilis in Miseno, Southern Italy.

capacity of almost 85,000 cubic metres (Figure 1(a)). Moreover, the use of columns in a Roman reservoir had just been introduced to Istanbul, ancient Constantinopolis. As a matter of fact, the Binbirdirek reservoir, covering an area of 3,640 m^2 and with a capacity of around 32,500 m^3 of water (66 × 56 metres), was carried by 224 columns consisting of 16 rows, each one having 14 columns all equal in length, with every column carrying the signature of its master ("1,001" was used to emphasize the great number of columns) (Figure 1(b)). Finally, in Figure 1(c) there is a spectacular view of the Piscina Mirabilis in Miseno (the ancient Misenum), in Southern Italy, which has to be considered the biggest Roman reservoir used for military aims ever known until now (supplying the Classis Praetoria Misenensis) with a volumetric capacity of 12,600 m^3 of water (De Feo *et al.* 2010a).

WATER DISTRIBUTION SYSTEMS

Water distribution systems are aimed at distributing water from reservoirs or aqueducts to the end users. The modern systems are based on the use of pipes. Regarding this aspect, the Minoan society was surprisingly "modern". As a matter of fact, in the Knossos palace, the water supply was furnished by means of a network of terracotta piping located beneath the floors at depths that varies from a few cm up to 3 m. Similar terracotta pipes were discovered in some other Minoan sites, such as Tylissos. Terracotta pipes have also been found at Vathypetro, as well as in the "Caravanserai" (Guest House), southern of the Knossos palace with some also having been found scattered in the countryside (Angelakis & Spyridakis 2010).

Roman aqueducts led water to an elevated city distribution tank, referred to as "*castellan*". The water mains departed from this point. Part of the water was allowed to overflow from the distribution tank in order to maintain a constant hydraulic head. The overflow water was used for street cleaning. Structures were mostly of masonry. While, the underground conduits through rocky ground were unlined. Those through friable soil were lined with a concrete mix of lime, pozzolan, and crushed brick. In the loosest soils, the conduits were lined with squared stones. Conduits had different cross-sectional shapes but were mostly rectangular, covered over with gabled or flat stone roofs. Water was tapped from castles through *fistulae*, lead or bronze pipe sections under permanent hydraulic load, which ensured a constant flow rate. Water flowed into the mains from the fistulae. No direct tapping from the aqueducts was allowed and water could be drawn only from the castles. Detailed regulations governed the arrangement of the fistulae to ensure the accuracy of water delivery (Martini & Drusiani 2009).

Water-supply facilities have a long history in China. In particular, developed water-supply facilities existed in ancient China, and the prosperous periods in Chinese history all had comprehensive water-supply planning and reasonable choice of water source. As a matter of fact, Du & Chen (2007) analyzed the highly comprehensive water system planning, water-supply facilities and the evolution of water-supply technology of cities in ancient China, including water-supply system consisting of a pipeline system and cleaning measures in the City of Yangcheng (of Eastern Zhou Dynasty), as well as the choice of water source and history of water-supply development of ancient Cities of Chang'an (modern Xi'an) and Beijing. While, Koenig & Fung (2010) focused on Lijiang City (at an altitude of 2,400 m in the northwest of Yunnan Province, China), which was assigned to the UNESCO World Heritage List on 6 December 1997, noting in particular that it "possesses an ancient water supply system of great complexity and ingenuity that still functions effectively today". Starting from the 13th century CE., the Old Town of Lijiang has built a unique water supply system, with spring collection works, a reservoir, spillway, water distribution network, weirs, gates and sluices, and other stone made hydraulic structures. It is worth noting that no similar systems have been found anywhere else in China (Koenig & Fung 2010).

FOUNTAINS

The Minoan civilization gave an extraordinary contribution to the development of water management practices also in terms of fountains. The main examples of Minoan fountains are subterranean structures supplied with water directly or from springs via ducts. The construction of steps or alternatively the shallow basins testify for the water to be directly taken out with the use of a container. This recalls the type of fountain of the later Classical and Hellenistic period called arykrene. The most typical of them is that of the Zakro palace. Another fountain similar to the Tykte was found at the "Guest House" (Caravanserai) of Knossos in the "Spring Chamber". A ritual function of the particular fountains is also argued, as artefacts of ritual content have also been unearthed. Another type known in later periods as rookrene, which constantly provided fresh water was also found in Zakro and with the two zoomorphic waterspouts was illustrated above as part of the closed/pressured pipe system. Finally, a remarkable fragment from a fresco composition depicting a fountain of a supposedly Minoan garden, proposed for several palaces, was found in the "House of Frescoes" in Knossos (Angelakis & Spyridakis 2010).

During the Roman period, public fountains were usually located in the street. For example, in Pompeii the fountains were located at fairly evenly spaced intervals of about 100 m, and it was rare for anyone to have to carry their water for more than 50 m (Hodge 2002). The simplest form of street fountain was normally equipped with an oblong stone basin, typically about $1.5 \times 1.8\,m^2$ and 0.8 m high, into which the spout discharged, and which presumably was normally full. The fountains were deliberately designed to overflow in order to clean the street (Hodge 2002; De Feo *et al.* 2009*b*). Not far from the city of Pompeii, in the District of Salerno, there is a Roman gallery in rock in the village of Sant'Egidio del Monte Albino in the basin of the Sarno river. The gallery was realized in order to supply a public fountain which stands on the structure of an ancient Roman villae (the Helvius villae). The Helvius fountain was a public fountain, but it was quite different from the public fountains in nearby Pompeii. As a matter of fact, the Helvius fountain was realized neither in a single block of white marble nor in limestone nor in Vesuvian stone.

It was not realized by means of matched slabs. Moreover, there is another particular aspect which differentiates our fountain from the Pompeian fountains. In fact, the Helvius fountain has a sculptural decoration on the three available sides (De Feo *et al.* 2009*b*).

The study of the ruins of Pompeii gives a clearer understanding of the Roman urban water supply. From the *castellum divisorium*, three mains lead the water to different parts of the city filling water towers (Figure 2). The water towers (*Castellum Secondarium* or *Castellum Privatum*) were lead tanks positioned over brick masonry pillars, 6 m tall, located at crossroads and connecting small numbers of customers. They also supplied public fountains. The single user had to pay to get some water for his premises (Monteleone *et al.* 2007).

The water was metered by means of bronze orifices, the calices connecting the customers pipes (usually *Quinariae* pipes) to the *castellum privatum* lead tank. In Pompeii, case calices were placed at the bottom of the lead tanks, and pipes fit into cavities left in the brick pillars. The *quinaria* pipe measured about 2.31 cm internal diameter. The lead tank of the water tower acted as a disconnection between the system at high pressure upstream and the customers' pipes downstream. In order to fit water derivation pipes elsewhere in the *castellum privatum* was against the regulations. The only connection available had to be arranged with the water office discussing the quantities for consumption. This water supply system clearly shows that water towers could break from the pressure built up in the mains descending from the initial *castellum* divisorium at the top point of the city, with excess water overflowing into streets drains. The maximum height of water "over the tap" was about 6 m, without accounting for the pressure losses in the delivering pipes (Monteleone *et al.* 2007).

Monteleone (2009) studied the features of fifteen street fountains in Pompeii in order to derive the maximum flow rate expected for each fountain. The maximum velocity estimated was within 3 and 6 m/s, while the idea of a most probable average flow rate was introduced, and the corresponding velocities resulted in the range 1.3 to 3 m/s. Assuming that "*Octonaria*" pipes supplied the fountains, the calculation of a maximum and average flow rate allowed an interpretation of the flow through a quinaria unit area, with a maximum average value of 164 m^3/d and a most probable average value of 83 m^3/d (Monteleone 2009).

DRAINAGE AND SEWERAGE SYSTEMS

Drainage systems were used for the disposal of surplus water, and were found both in cities, to carry rainfall, overflow from fountains and bathrooms and in the country, to prevent flooding in the fields. Sewerage systems were used for the conveyance of domestic wastewater, and were only found in cities, where they were necessary due to a high population density (Hodge 2002). However, in most cases, combined systems of flowrates composed mainly of rainfall runoff and wastewater were applied.

The Minoan civilization gave an extraordinary contribution to the development of water management practices also in terms of drainage and sewerage systems. As a matter of fact, Minoan palaces were equipped with elaborate storm drainage and sewer systems. Open terracotta and stone

Figure 2 | The *castellum divisorium* in Pompeii.

conduits were used to convey and remove stormwater and limited quantities of wastewater. Pipes, however, were scarcely used for this purpose. Larger sewers, sometimes large enough for a man to enter and clean, were used in Minoan palaces at Knossos, Phaistos and Zakro. These large sewers may have led to the conception of the idea of the labyrinth, the subterranean structure in the form of a maze that hosted the Minotaur, a hybrid monster. Some palaces had toilets with flushing systems operated by pouring water in a conduit. However, the best example of such an installation was found on the island of Thera (Santorini) in the Cyclades, Greece. This is the most eloquent and best-preserved examples belonging to the LMIA (*ca.* 1550 B.C.) in the Bronze Age settlement of Akrotiri, which shares the same cultural context of Crete (Angelakis & Spyridakis 2010).

At the beginning, for some centuries, the collection and discharge of rainwater runoff was managed separately by wastewater. As a matter of fact, rainwater was carried in simple canals carved into the rock in cities with bedrock (i.e. the Acropolis of Athens). Otherwise, the canals were covered with rocks. A system for the simultaneous discharge of both rainwater and domestic sewage was realized in the Greek period (Tolle-Kastenbein 2005).

Ancient drainage and sewerage systems were usually developed on four levels. The initial canals coming from buildings (first order) ended in street canals of second order, which prosecuted in principal canals with an increasing size (third order) and ended in a final huge collection channel (fourth order), usually present only in big cities. The *great drain* of Athens was first realized as a rainwater drainage system. But, in the first quarter of the 5th Century B.C. it received domestic sewage and ended in a huge collection channel (fourth order) similar to the Roman *Cloaca Maxima* (Tolle-Kastenbein 2005).

The Cloaca Maxima is the best known ancient urban drain. Tradition ascribes its construction to Tarquinius Priscus, king of Rome 616–578 B.C. The *Cloaca Maxima* (4.2 m high, 3.2 m wide) was covered by stone vaulting, while its bottom was paved with basalt pavers. It combined the three functions of wastewater and rainwater removal and swamp drainage. As it is well known, the exit from the *Cloaca Maxima* drain into the river Tiber still exists in Rome, but now partly hidden by the modern Lungotevere Embankment (Hodge 2002).

The street drains of Pompeii are very famous. At the time of the famous Vesuvius eruption, the drains existed only in the area around the forum. The streets were a sort of open channel conveying water coming from public fountains, rainwater and segregate sewage. Therefore, as shown in Figure 3, in the streets there were raised sidewalks (50–60 cm high) with stepping stones (*pondera*) at the street corners to enable pedestrians to cross from one side to the other without stepping down (Hodge 2002).

Figure 3 | Stepping stones (*pondera*) in Pompeii.

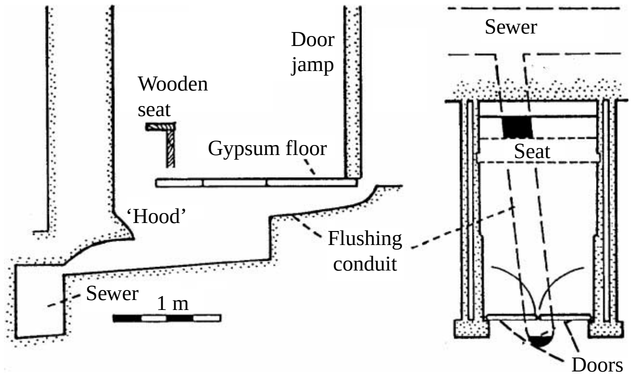

Figure 4 | Section and Plan of Ground-floor Toilet in the Residential Quarter of Palace of Minos (Angelakis *et al.* 2005).

TOILETS AND OTHER PURGATORY STRUCTURES

Toilets have a long history. The first evidence of the purposeful construction of bathrooms and toilets in Europe comes from Bronze Age Minoan (and Mycenaean) Crete in the second millennium B.C. (Vuorinen *et al.* 2007). In the palace of Knossos, rainwater was probably used to flush the toilet near the Queen's Hall (Figure 4).

The Hellenistic period is considered as the more progressive for the sanitary and purgatory engineering during the antiquity, although the considerable spreading of these systems during the Roman era. The Romans applied the earlier techniques in larger constructions, using the advantages of their building methods with concrete based walls and vaulted roofing. Moreover, due to their improved aqueduct technologies, they could provide natural water flow in most public latrines. It is also evident that such structures and installations have survived until the end of the ancient world and have been implemented during the beginning of the Byzantine period. The customs of the new religion, Christianity, modified some of the structures in terms of privacy in bathing facilities (Antoniou & Angelakis 2009).

Toilets during the Roman era can be divided into two groups: public and private. A public toilet was frequently built near to or inside a bath so that it was easily entered from both inside and outside of the bath. The abundance of water that was conducted to the bath could also be used to flush the toilet. Piped water for flushing private toilets seems to have been a rarity. The Romans, however, lacked something similar to our toilet paper. They probably commonly used sponges or moss or something similar. In public toilets, the facilities were common to all. They were cramped, without any privacy, and had no decent way to wash one's hands. The private toilets most likely lacked running water and they were commonly located near the kitchens. All this created an excellent opportunity for the spreading of intestinal pathogens (Vuorinen *et al.* 2007). In many cases, the private toilet was located near the kitchen. Hygienic conditions in both types of toilets must have been very poor, and consequently intestinal diseases were diffused. Dysentery, typhoid fever and different kinds of diarrhoeas are likely candidates for diagnoses. Descriptions of the intestinal diseases in the ancient texts are unfortunately so unspecific that the identification of the causative agent is a very problematic venture. Studies of ancient microbial DNA might offer some new evidence for the identification of microbes spread by contaminated water (Vuorinen 2010).

IRRIGATION SYSTEMS

In general, irrigation can be defined as the artificial supply of water to supplement natural precipitation (or substitute for it) for the purpose of agricultural production (Bazza 2007). A key feature of irrigation is its expansionist tendencies. Countries that rely on irrigation for their agricultural production, and economic growth, tend to want to maximise their ability to reap the benefits by expanding the area under irrigation. Most development loans for irrigation focus on increasing the irrigable area by capturing and delivering more water to more land (Alam *et al.* 2007).

The Near East region extends from Turkey in the north to Somalia in the south and from Mauritania in the west to Afghanistan in the east. It is characterized by aridity and scarcity of water which explains its dependence on irrigation since ancestral times (Bazza 2007). Irrigation has been practiced in this region for more than 5,000 years. In fact, harnessing water resources and mastering their use were the backbones of development and prosperity of most early civilizations in the region. Irrigation in this region can be considered one of the origins of this practice and its diffusion to the rest of the world. The earliest irrigation practice started in Egypt, with flood irrigation from the Nile River, before gradually evolving to the use of water lifters powered by humans, animals and the flow of water. The technique of artificial irrigation was later introduced in Mesopotamia and Iran, at least 3,500 years ago, before spreading to different neighbouring regions, particularly westward to North Africa and the Mediterranean (Bazza 2007).

Noteworthy, organised irrigation has been practiced in Central Asia along the rivers Amu Darya and Syr Darya for over 1,300 years. The Otrar oasis is located on the middle Syr Darya river near the confluence with the Arys river. This rich complex of channels, oxbow lakes and shifting floodplains formed the site of the Oasis of Otrar, a key settlement in Central Asia on one of the routes of the Silk Road. Remnants of irrigation works were discovered in the middle and lower reaches of the main rivers Syr Darya, Talas and Chu, starting as long ago as the 5th Century B.C. The region is still being used for crop production and following the introduction of large-scale irrigation systems in the 1950s and 1960s has caused well known problems, including over abstraction of water from rivers, inefficient irrigation, salinisation of agricultural lands, reduced inflows into the Aral Sea and the associated problems of desertification (Clarke *et al.* 2010). Clarke *et al.* (2010) showed how modern hydraulic software, which is normally used for the design of river flood embankments, can be used to understand the operation of ancient canal networks. In particular, the authors were are able to understand why the canals initially were limited in size and as greater areas were to be irrigated it became necessary to move the connection between the canals and the river upstream. At the same time, lower lying areas which became prone to salt accumulation in the soils were gradually abandoned after some *ca*.100 to 1,200 years of irrigation (Clarke *et al.* 2010).

Tung & Pai (2009) surveyed the development of irrigation canals and its influence on agricultural society in Taiwan from 1624. During the Holland-Spain period and Ming-Cheng Period (1624–1683), only ponds and small scale irrigation canals were built. During the Qing Dynasty (1683–1895), four important irrigation canals including the Babao canal, Babuza canal, Liukon canal, and Tsaokon canal were established. During the Japanese Occupation period (1895–1945), the Taoyuan Canal and Chia-Nan canal were established. After the Taiwan retrocession, the representative Shihmen canal was constructed. Through the spatial cognition of irrigation system, different agricultural social groups formed their own life style, characteristics, and even culture. In addition, the irrigation range enforced the identity and territoriality of the social group. From the Qing Dynasty, irrigation canals also played a main role in social agricultural construction and classification of social strata (Tung & Pai 2009).

QANATS AND SIMILAR SYSTEMS

As it is well known, qanats are underground channels consisting of verticals shafts connected at their bottom with a sub-horizontal tunnel bringing water from an aquiferous stratum. The underground tunnel has a slight downward slope useful for the water tapped to run down it and into the open air by gravity (Hodge 2002; Moosavi 2006; Stiros 2006; De Feo *et al.* 2010*b*). These are generally called *qanats*, a term in currently use in Iran, but also have other names and are found in many regions from Asia to Europe, Africa, America and also Oceania with the names of: *qanat* in Irak and Iran; *karez* in China and along the Silk Road; *falaji* in Oman; *khottara* in Morocco; *foggara* in Algeria; *guettara, m'louka,* in Tunisia; *madjirat, cimbras, minas, zanias* in Spain; *cunicoli, ingluttati, bottini* in Italy: *mambo* in Japan. The word "qanat" derives from an ancient Semitic word meaning "to dig", with there being several variations of the name and numerous differences in spelling (Hodge 2002; Tolle-Kastenbein 2005; Javan *et al.* 2006; Moosavi 2006; Stiros 2006; De Feo *et al.* 2010*b*). Qanats were first developed in the area spanning from Kurdistan and Baluchistan, as the outcome of an experience in digging surface channels and wells, and to the development of mining techniques (Foltz 2002). A qanat system can be composed of several branches joined forming a network (De Feo *et al.* 2010*b*). Although the tunnel is the heart and raison d'être of the qanat, vertical shafts have most outward and visible manifestations (Hodge 2002). The shafts are usually spaced 20–40 m (de Bustamante *et al.* 2006; Javan *et al.* 2006). Qanats exist in more than 34 countries all over the world, but most are concentrated in present day Iran, which has about 30,000 active systems with a total annual discharge of about 9 billion m^3 (Moosavi 2006).

It is wrong to regard such works, which we may generally describe as *draining tunnels,* as a homogeneous technique applied with different names in different countries. They are instead the products of complex procedures, the point of arrival of diverse experiences developed in different areas and adapted to local geographical situations, so much so as to operate with various methods through space and time. We must bear in mind the great differences in the functioning systems of the various *qanats* within Iran itself and in the various countries, and also of the change in the ways of operating of the same tunnel in different seasons and climatic conditions, through the ages.

Over the last 1,000 years in Turkmenistan and Tarim groundwater systems have been constructed on desertic sloping piedmonts: the "karez" system. They are still active today in Iran, Turkmenistan and Tarim in the arid region near the ancient city of Turkestan in Kazakshtan (Sala *et al.* 2010). A karez line is not intended for transporting, by gravity and underground galleries, the groundwater stock from a localized aquifer downslope until emergence but for raising by differential pressure the water table of wells along the whole itinerary of the line. Karez wells, dug down into a water-bearing layer, are mouths through which groundwater is lifted to the surface by the interaction of two principles of water dynamics: hydrostatic pressure and gravity. Wells, dug into a shallow semi-confined aquifer having differential pressure, act by as micro-artesian wells. Aligned along a moderate slope and interconnected though natural horizontal strata of pebble deposits, they work by gravity as a sequence of connected vessels. The action of the two principles means that water comes out from a certain point of the line, depending on the groundwater stock and the season (Sala *et al.* 2010).

CONCLUSIONS

The following (general and particular) outcomes on the topic of water and wastewater technologies in ancient civilizations can be stated.

(a) The ancient water management techniques to contest drought and desertification in the Mediterranean constitute an extraordinary repository of biological diversity and sustainable knowledge, the heritage of local population and producers (Laureano 2010).

(b) Each fortified city built during the Bronze and Iron Ages had its own urban supply system, which was an inseparable part of planning and execution during building of the city (Tsuk 2010).

(c) The meaning of sustainability in modern times should be revaluated in light of ancient public works and management practices (Angelakis & Spyridakis 2010).

(d) The *Piscina Mirabilis* in *Misenum* in Southern Italy can be considered the biggest Roman reservoir used for military aims ever known up until now with a volumetric capacity of 12,600 m^3 (De Feo *et al.* 2009*b*).

(e) The average flowrate of the 19.7 km Roman tunnel constructed under the Bologna hills was probably around 0.55–0.56 m/s, with a mean velocity of about 0.59 m/s (Drusiani *et al.* 2010).

(f) As a municipality located in the hinterland of the *caput mundi*, Formia may be regarded as a typical example of management and public and private use of water resources during the Roman period (Ciccone *et al.* 2010).

(g) The Etruscan tunnel called *Ponte Coperto* near the town of Cerveteri (about 45 km north-west of Rome) is an impressive example of the Etruscan skill in water management as well as the fact that the Roman building and water engineering has its roots in Etruscan hydraulic work (Bersani *et al.* 2010).

(h) Yzeron, Aspendos and Barratina are three great examples of inverted siphons that have successfully functioned for several hundred years, highlighting the skill of Roman engineers in hydraulic applied to solving morphological problems of the territory (Temporelli & De Novellis 2010).

(i) A Roman public toilet was often built in proximity to or inside a bath. While, a Roman private toilet was (in many cases) located near the kitchen. Therefore, the hygienic conditions in both types of toilets must have been very poor (Vuorinen 2010).

(j) At the present, most major cities in China are facing issues related to drainage systems and city water systems. These cities are often hindered by floods and other water-related problems. Learning from their ancestors' experience would be important for modern planners and decision makers (Du & Zheng 2010). In addition, starting from the 13th century, the Old Town of Lijiang in China has built a unique water supply system, with spring collection works, a reservoir, spillway, water distribution network, weirs, gates and sluices, and other structures which met the needs of the inhabitants until the end of the 20th century (Koenig & Fung 2010).

(k) Modern hydraulic software, which is normally used for the designing of river flood embankments, can be used to understand the operation of ancient canal networks (Clarke *et al.* 2010).

(l) In Italy, Sicily is usually cited for its "Ingruttati", but also in the Campania Region there are some qanats ("Qanate") even though they were not known of (De Feo *et al.* 2010*b*). Also, the "karez" are not qanat but constitute a now-forgotten hydraulic device working by a combination of more complex principles (Sala *et al.* 2010).

REFERENCES

Alam, U., Sahota, P. & Jeffrey, P. 2007 Irrigation in the Indus basin: a history of unsustainability? *Water Sci. Technol. Water Supply* **7**(1), 211–218.

Angelakis, A. N. & Spyridakis, S. V. 1996 The status of water resources in Minoan times: a preliminary study. In: Angelakis, A. N. & Issar, A. S. (eds) *Diachronic Climatic Impacts on Water Resources with Emphasis on Mediterranean Region*. Springer-Verlag, Heidelberg, Germany, pp. 161–191 (Ch. 8).

Angelakis, A. N. & Spyridakis, D. S. 2010 Water supply and wastewater management aspects in Ancient Greece. *Water Sci. Technol. Water Supply* **10**(4), (in press).

Angelakis, A. N., Koutsoyiannis, D. & Tchobanoglous, G. 2005 Urban wastewater and stormwater technologies in ancient Greece. *Water Res.* **39**, 210–220.

Angelakis, A. N., Savvakis, Y. M. & Charalampakis, G. 2007 Aqueducts during the Minoan Era. *Water Sci. Technol. Water Supply* **7**(1), 95–101.

Antoniou, G. P. & Angelakis, A. N. 2009 Historical development bathrooms (toilets) and other sanitary and purgatory structures in Greece. *Proceedings CD of 2nd IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies*, Bari, Italy, 28–29 May 2009.

Bazza, M. 2007 Overview of the history of water resources and irrigation management in the Near East region. *Water Sci. Technol. Water Supply* **7**(1), 201–209.

Bersani, P., Canalini, A. & Dragoni, W. 2010 First results of a study of the etruscan tunnel and other hydraulic works on the "Ponte Coperto" stream (Cerveteri, Rome, Italy). *Water Sci. Technol. Water Supply* **10**(4), (in press).

Ciccone, S., Di Leo, A. and Tallini, M. 2010 Groundwater exploitation for public and private uses in the towns of the roman province: the emblematic example of Formia (Latium Adiectum Central Italy). *Water Sci. Technol. Water Supply* **10**(3), 394–402.

Clarke, D., Andrews, P., Messeth, E., Sala, R. & Deom, J.-M. 2010 Analysis of the hydraulics of the irrigation canals of Otrar, Kazakhstan. *Water Sci. Technol. Water Supply* **10**(3), 453–461.

de Bustamante, I., Iglesias, J. A., López-Camacho, B., Sanz, J. M., Garcia-Calvo, E., Martin-Crespo, T., Ortiz-Gómez, D. & Lillo, F. J. 2006 The Ocana's Qanat and "Fuente Grande": A Cultural Heritage to Preserve. *Proceedings of 1st IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies*, Iraklio, Greece, 28–30 October 2006, ISBN 960-88296-2-3, pp. 509–515.

De Feo, G. & Napoli, R. M. A. 2007 Historical development of the Augustan Aqueduct in Southern Italy: twenty centuries of works from Serino to Naples. *Water Sci. Technol. Water Supply* **7**(1), 131–138.

De Feo, G., Malvano, C., De Gisi, S. & De Biase, O. 2009*a* The ancient aqueduct from Serino to Beneventum, in southern Italy: A Technical and Historical Approach. *Proceedings CD of 2nd IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies*, Bari, Italy, 28–29 May 2009.

De Feo, G., De Gisi, S., Malvano, C., Tortora, A., Del Prete, S., Maurano, F. & Tropeano, E. 2009*b* The Roman Aqueduct and the Helvius' Fountain in Sant'Egidio del Monte Albino, in Southern Italy: a Historical and Morphological Approach. *Proceedings CD of 2nd IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies*, Bari, Italy, 28–29 May 2009.

De Feo, G., De Gisi, S., Malvano, C. & De Biase, O. 2010*a* The greatest water reservoirs in the Ancient Roman World and the "Piscina Mirabilis" in Misenum. *Water Sci. Technol. Water Supply* **10**(3), 350–358.

De Feo, G., De Gisi, S., Malvano, C., Capolongo, D., Del Prete, S., Manco, M., Maurano, F. & Tropeano, E. 2010*b* Historical, biological and morphological aspects of the Roccarainola Qanat in the district of Naples, Italy. *Water Sci. Technol. Water Supply* **10**(4), (in press).

Drusiani, R., Leoni, G., Demaria, D. & Lembo, N. 2010 Water supply of Bologna (Italy) by Roman Aqueduct: history, morphology and hydraulic, from ancient time to nowadays. *Water Sci. Technol. Water Supply* **10**(4), (in press).

Du, P. & Chen, H. 2007 Water supply of the cities in ancient China. *Water Sci. Technol. Water Supply* **7**(1), 173–181.

Du, P. & Zheng, X. 2010 City drainage in ancient China. *Water Sci. Technol. Water Supply* **10**(4), (in press).

Foltz, R. C. 2002 Iran's water crisis: cultural, political, and ethical dimensions. *J. Agric. Environ. Ethics* **15**, 357–380.

Hodge, A. T. 2002 *Roman aqueducts & water supply*. 2nd edition. Gerald Duckworth & Co. Ltd, ISBN 0715631713, London, UK.

Javan, A., Hassanli, A. M. & Shahrokhnia, M. A. 2006 The ancient qanats of Iran. *Proceedings of 1st IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies*, Iraklio, Greece, 28–30 October 2006, ISBN 960-88296-2-3, pp. 531–534.

Khajeh Abdollahi, M. H. 2006 Ancient Hydro-strictures for water management in Chogha Zanbil, Shustar and Dezful, Iran. *Proceedings of 1st IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies*, Iraklio, Greece, 28–30 October 2006, ISBN 960-88296-2-3, pp. 239–245.

Koenig, A. & Fung, S. C. C. 2010 Ancient water supply system of the old town of Lijiang, Yunnan Province, China. *Water Sci. Technol. Water Supply* **10**(3), 383–393.

Koutsoyiannis, D., Zarkadoulas, N., Angelakis, A. N. & Tchobanoglous, G. 2008 Urban water management in Ancient Greece: legacies and lessons. *ASCE J. Water Resour. Plann. Manage.* **134**(1), 45–54.

Laureano, P. 2000 *The Water Atlas. Traditional knowledge to combat desertification*, Laia Libros.

Laureano, P. 2006 Ancient water catchments techniques for proper management of Mediterranean ecosystems *Proceedings of 1st IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies*, Iraklio, Greece, 28–30 October 2006, ISBN 960-88296-2-3, pp. 209–218.

Laureano, P. 2010 Ancient water management techniques to contrast drought and desertification in the Mediterranean. *Water Sci. Technol. Water Supply* **10**(4), (in press).

Martini, P. & Drusiani, R. 2009 History of the water supply of Rome as a paradigma of water services development in Italic Peninsula. *Proceedings CD of 2nd IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies*, Bari, Italy, 28–29 May 2009.

Mavromati, E. & Chryssaidis, L. 2007 Aqueducts in the Hellenic area during the Roman Period. *Water Sci. Technol. Water Supply* **7**(1), 139–145.

Monteleone, M. C. 2009 Fountains in the streets of Pompeii: the evaluation of the outlet velocity and of the expected flowrate from the features of fifteen fountains. *Proceedings CD of 2nd IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies*, Bari, Italy, 28–29 May 2009.

Monteleone, M. C., Yeung, H. & Smith, R. 2007 A review of Ancient Roman water supply exploring techniques of pressure reduction. *Water Sci. Technol. Water Supply* **7**(1), 113–120.

Moosavi, S. A. A. 2006 Qanat Invention Puzzle. *Proceedings of 1st IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies*, Iraklio, Greece, 28–30 October 2006, ISBN 960-88296-2-3, pp. 535–540.

Parise, M. 2009 Distribution and characteristics of ancient underground aqueducts in Italy. *Proceedings CD of 2nd IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies*, Bari, Italy, 28–29 May 2009.

Sala, R., Deom, J. M. & Clarke, D. 2010 The Karez of the Sauran Region. *Water Sci. Technol. Water Supply* **10**(4), (in press).

Stiros, S. C. 2006 Accurate measurements with primitive instruments: the "paradox" in the qanat design. *J. Archaeol. Sci.* **33**, 1058–1064.

Temporelli, G. and De Novellis, F. 2010 Aspects of hydraulic engineering concerning inverted siphons used in roman age. *Water Sci. Technol. Water Supply* **10**(3), 445–452.

Tolle-Kastenbein, R. 2005 *Archeologia dell'acqua (Water archaeology)*. Longanesi-Collana Biblioteca di archeologia. ISBN 8830411655, Italy.

Tsuk, T. 2010 Urban water reservoirs in the land of the Bible during the Iron Age (1000 BCE-586 BCE). *Water Sci. Technol. Water Supply* **10**(4), (in press).

Tung, Y. T. & Pai, T. Y. 2009 Aboriginal people mutual aid for water supply in Taiwan-from ancient to modern time. *Proceedings CD of 2nd IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies*, Bari, Italy, 28–29 May 2009.

Vuorinen, H. S. 2010 Water, toilets and public health in the roman era. *Water Sci. Technol. Water Supply* **10**(3), 411–415.

Vuorinen, H. S., Juuti, P. S. & Katko, T. S. 2007 History of water and health from ancient civilizations to modern times. *Water Sci. Technol. Water Supply* **7**(1), 49–57.