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in the Mediterranean Region

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Preface of the Editor

The Deutsche Wasserhistorische Gesellschaft (DWhG), or German Water History Association, is a non-commercial organisation that fosters knowledge and awareness of the history of water management and hydraulics. To do so, DWhG organises conferences and publishes books and proceedings on related topics. DWhG has roughly 400 members worldwide, all interested in the history of water, and representing all scientific fields, from engineering and hydrology to archaeology and history, as well as humanistic studies. This interdisciplinary convergence often triggers new ideas, insights, and solutions for particular problems or questions. Since its foundation in 2002, the DWhG has published 26 volumes, most of which cover a special regional or temporal aspect. Additionally, 16 special volumes – mostly monographs – have been published. This enormous coverage indicates the need for scientific literature dealing with water history at the interface of the sciences and humanities.

This volume contains the proceedings of the 16th *Cura Aquarum* International Conference on the History of Water Management and Hydraulic Engineering in the Mediterranean Region, held in Athens, Greece, from the 28th to 30th of March 2015. This conference was organised jointly by Anna Androvitsanea and Henning Fahlbusch, who recruited participants conducting research on various aspects of ancient water management in Greece.

Consequently, the evolution of water management in Greece is subject of most of the contributions, which cover all phases from the Minoan and Mycenean periods to recent water supply systems. Five papers deal with the water management of particular parts of Athens, allowing for a better understanding of the development of that city's infrastructure. Case studies from Corinth, Olympia, Naxos, Megara, and Piraeus complement this coverage. As pointed out by Henning Fahlbusch, in both his keynote lecture in Athens and in his contribution to the proceedings, Greece can be regarded as the cradle of water management in Europe. The other reports within this volume certainly support this hypothesis.

This volume is completed by case studies from across the Mediterranean region (e.g., Israel) as well as a compilation of hydraulic structures used for sewage and water supply systems in Egypt. Further contributions focus on special topics like ancient water clocks, Roman lead pipes, qanats, and other hydraulic features. This broad variety of topics reflects the importance of water-studies in very diverse disciplines across engineering, the natural and social sciences, and the humanities.

This is the first time that the conference proceedings published by DWhG have not been not edited by Christoph Ohlig. It was my great honour to work with him to learn how to do the editorial work. He taught me his diligent and thorough way of working. Editing this volume, I have gained new appreciation for how much labour and time he invested in more than 15 years of publishing the more than 40 volumes that precede this one. It is due to his dedication that the published series of DWhG has become such a success. And it is due to the handing over of this editorship, that authors and colleagues had to wait quite a long time until these proceedings were finally finished.

Kai Wellbrock

Siegburg, December 2017

Preface of the Conference Organisers

It was our great pleasure to be able to organise the sixteenth *Cura Aquarum* conference in Athens. When the first meeting on water supply in antiquity was held at Koblenz, Germany, in 1975, at the initiative of Bernd Haberey (Cologne) and on behalf of the Leichtweiss-Institute for Hydraulic Research of the TU Brunswig, as well as of engineers from the Studienkreis für die Geschichte des Wasserbaus, der Wasserwirtschaft und der Hydrologie, none of the participants could have imagined that it would be the beginning of a such a great series of conferences. Yet, here in Athens, we celebrate its 40th anniversary. The first conference abroad already took place in 1977, in Lyon (France). All subsequent events have been carried out in countries around the Mediterranean Sea. In 1991 our colleagues from the Netherlands, the "Dutch nymphs" who organised two conferences, came up with the title *Cura Aquarum*, which we keep up to this day.

The main organiser has, however, changed. Today the Deutsche Wasserhistorische Gesellschaft (DWhG), or German Water History Association, serves as a successor of the aforementioned group of engineers. During its 12 years of existence, the DWhG has organized 25 conferences on various aspects of the history of water management.

It would be more or less impossible to plan a conference in a foreign country without a local partner. For this reason, we were delighted that the German Archaeological Institute in Athens (DAI Athens) helped us with words and deeds, as they also had done in 1981. We are grateful to Katja Sporn and Reinhard Senff for this support. Their assistance was essential, not only for compiling an interesting programme of lectures, but also for the excursions to the Kerameikos and Olympia. We also take this opportunity to thank all of the speakers for the presentation of their research. Meanwhile, we must apologise for any mistakes in the translation of the various abstracts. Unfortunately, English is not our mother tongue, and we admit that we do not qualify as professional translators. At the very least, we hope that we were able to preserve the meaning of the original texts.

Since the meeting in Koblenz, an excursion to view ancient projects of hydraulic engineering has become an integral part of every conference. We have mostly chosen destinations which one cannot visit as "a regular tourist", and we observed this tradition here again in Greece. Needless to say, visiting the places of interest would not have been possible without the support of the people who care for them. We would therefore like to extend a heartfelt thank you to the Ephorates of Athens, East Attica, West Attica & Piraeus, and Corinth, and representatives of the various excavation sites for their understanding and support, most notably Eleni Banou, Anastasia Lazaridou, Stella Chrisoulaki and Konstantinos Kissas.

The goal of the conference, including the lectures and excursions, is to bring scientists from various disciplines together for a fruitful exchange of ideas. One of the excursions during the fourth *Cura Aquarum* in 1981 included the Kopais project, which was presented at that time by Siegfrid Lauffer (University Munich). That visit would inspire Jost Knauss (TU Munich) to get involved in the history of the Kopais plain and, later, in the Mycenaean hydraulic engineering of Greece, in general. It is with particular pleasure that we include at least four projects that he investigated among this year's destinations. Naturally, we hope that similar initiatives might spring from this meeting.

Seldom do participants of such a large congress like the sixteenth *Cura Aquarum* imagine the amount of preparatory work "behind the curtain". The organisers would have been hopelessly overwhelmed if our friend Stefania Kostourou of Marine Tours had not supported us in a professional and reliable way. We thank her wholeheartedly for her contributions to our endeavour.

Anna Androvitsanea — Henning Fahlbusch

Athens, March 2015 — *Ratzeburg, March 2015*

The history of the *Cura Aquarum* conferences

1st	1975	Koblenz, Germany
2nd	1977	Lyon, France
3rd	1979	Istanbul, Turkey
4th	1981	Athens, Greece
5th	1983	Jerusalem, Israel
6th	1985	Cairo, Egypt
7th	1988	Rome, Italy
8th	1991	Merida, Spain
9th	1994	Pompeii, Italy
10th	1998	Syracuse, Italy
11th	2001	Jerusalem, Israel
12th	2004	Ephesus, Turkey
13th	2007	Petra, Jordan
14th	2009	Toledo, Spain
15th	2012	Jerusalem, Israel
16th	2015	Athens, Greece

Qanats, the mother of all aqueducts?

Wilke D. Schram

Abstract

On a superficial view the Persian qanat might be considered as the predecessor of the Roman aqueduct. But is that a good observation? Apart from qanats and aqueducts there are qanat fed aqueducts and aqueducts with a subterranean water source. What are the essential differences between these ancient water supply systems? We have to be careful making general remarks about such ancient water systems which stem from 500 - 2800 years ago and are scattered over an area from England in the west to China in the east. Further we have to take into account that contrary to (some) aqueducts, by far the most qanats are archaeologically not well researched.
If one looks into the details, there are indeed similarities but even a considerable number of differences. Analogies and differences were already discussed by other scholars like Hodge, Castellani, and Voudouris.
We start here with basic descriptions of Persian qanats and Roman aqueducts, followed by a comparison of physical geographical, technological and societal characteristics of both systems. This brings us to some interesting conclusions where we define the essentials of both water supply systems.

1 Persian qanats

A qanat is a water supply system, a combination of an infiltration gallery that collects water from an aquifer[1], and an underground tunnel, connecting a series of vertical shafts, to transport water by gravity to the surface for direct consumption and / or irrigation (fig. 1 & fig. 2). A qanat does not affect the hydrological and ecological equilibrium in a region for it is not possible to draw more water from the system (output-side) than is supplied by rivers and precipitation (input-side).
On the ground a qanat can easily be recognized as a series of mole-hills in an almost straight line (fig. 3). What one sees is the spoil dumped around the tops of the shafts as a result of the digging of the shafts and the channel. After construction the shafts are used during operation for access for maintenance and repair, and sometimes to draw water.

[1] An aquifer is an underground water bearing layer of permeable rock, gravel, sand, or silt from which groundwater can be extracted.

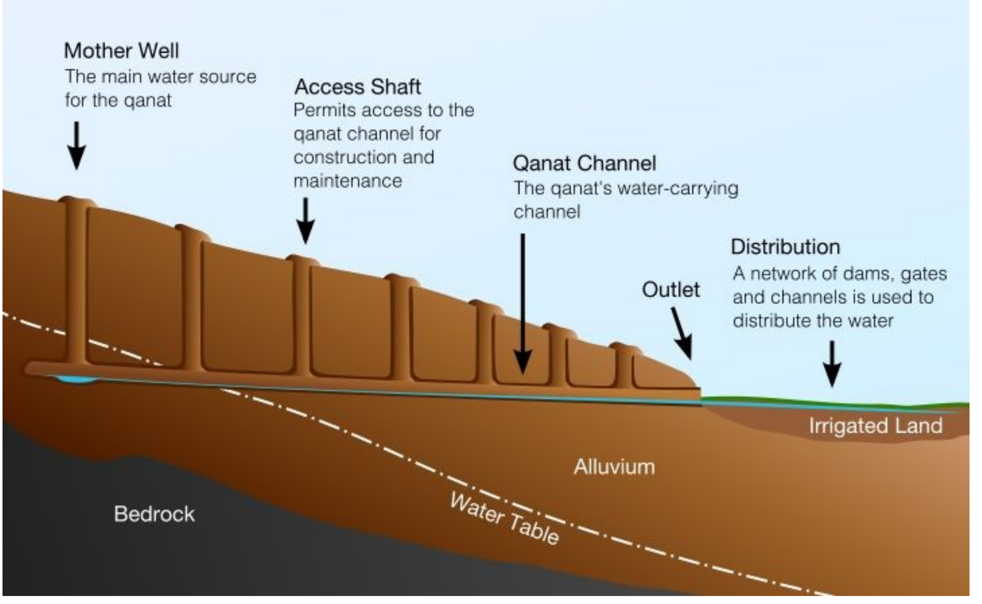

Fig. 1: The basic scheme of a qanat (the horizontal channel) with at left the aquifer and the mother well and at right the outlet where the water distribution takes place. Note the many vertical access shafts (source: Wikipedia).

Fig. 2 (top): View into the channel of a qanat, seen from the top of a vertical access shaft (source: Wikipedia).

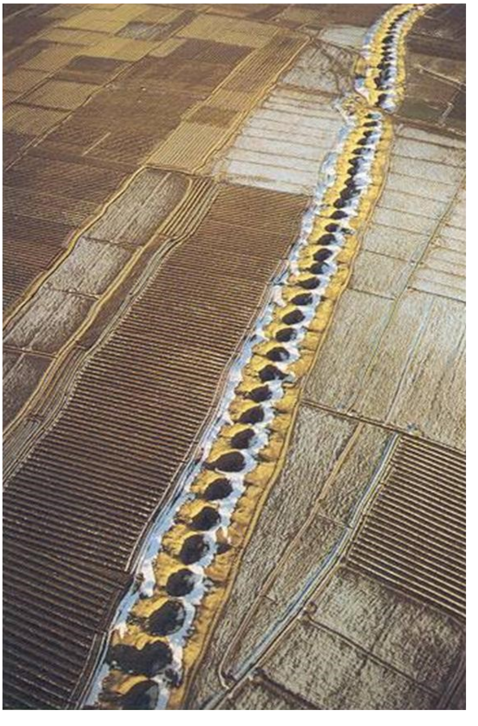

Fig. 3 (right): What looks like a line of craters is in fact an aerial view on the tops of the access shafts of a subterranean qanat.
(source: www.muslimheritage.com).

Traditionally its origin stems from NW Iran; during the 8th cent. BCE qanats were already in use to dewater ore mines; Sargon the 2nd (714 BCE) reports already about qanats. Often qanats can be found in hot, arid and semi-arid regions. This system of water supply was first spread to other parts of Iran and neighboring countries, later on to the east via Afghanistan to China (Turpan area) and to the west: Iraq, Syria, Jordan, partly to present Israel, and Cyprus, but also to the Arabian peninsula, Egypt, North Africa and Spain and possibly to some other area's in Europe. From Spain the qanat technique was brought to the Middle and South America's (Mexico, Peru, and Chile).

The construction of a qanat starts with the determination of the best place for a 'mother well' by means of (a) pilot shaft(s). This can only be done by very experienced persons, with knowledge of geology, morphology, hydrology and botany (special types of plants can hint on water hidden deep - up to 20 meter - under the surface. Then the course to the destination had to be established. The actual construction starts with digging the first vertical shafts, at 20 - 50 m distance from each other, from the lower end up to the mother well, on the appropriate level.

At the destination water is mainly used for consumption and for irrigation. If the qanat is still subterranean after arriving in the town, a special facility with stairs is created to make it possible for the public to draw water, called a payab (literally 'bottom of the ocean').

For maintenance and distribution a well-balanced social structure, management and governance are needed. Sometimes a private 'investor', but more often a group of landowners takes the initiative. After construction - which can take several years - a keen, time-sharing distribution scheme is established based on a cycle that consists of a specific number (6 - 20) of days and night, embedded in oral tradition or written documents. The actual distribution is realized by masonry channels and sluice gates, and in urban settings, pipes.

There are more threats than only wartime troubles: maintenance is critical and neglect may cause subterranean collapse. Earthquakes often result in a breakdown of the qanat - remember the earthquake in Bam (Iran) on December 26, 2003 when 25.000 people were killed, 30.000 injured, and many qanats severely damaged which was disastrous for the date plantations.

Since the introduction of mechanical water pumps, there is a more slumber, but deadly threat: the gradual lowering of the groundwater table and depletion of the aquifers. In the early stages of decay efforts may be undertaken to add extra subterranean sources and lowering the channel bottom, but in the long run, this is a lost position. All this makes many qanats useless. The total absence of maintenance will result in subterranean collapses that make any future revitalization impossible. The net effect is a dependency on capital, technical skills, import of fuel, and supplies for maintenance of the machinery.

In modern aqueduct literature often the term ‘qanat technique’ or ‘qanat construction’ is used, to point at the use of vertical shafts to facilitate the construction of an aqueduct channel through a hill. Applications can be found in Droverberg and Brey (Germany), Walferdange (Luxembourg), Carhaix (France). This does of course not imply that in those cases a qanat is present.
Because of its subterranean nature, there are not many works of art attached to a qanat. By exception a bridge was necessary to bring the water on the right spot(s), like the one near Kharanaq (Yazd region, Iran, fig. 4). Less visible are subterranean dams to block the qanat channel. Qanats give a constant water flow but the demand is seasonal: for irrigation more water is needed in spring and summer and less in winter time so then it is better to interrupt the water flow. Even in early days water power was used for other purposes like for graining of floor and olives by attached millstones. Subterranean water mills are known from among others the Yazd region (Iran).

Fig. 4: Because of its subterranean nature there are not so much works of art attached to qanats. Here one of the exceptions: a qanat bridge near Kharanaq (50 km N of Yazd, Iran) (source: www.panoramico.com).

Badgirs, wind towers or wind catchers are used as natural ventilation for cooling rooms and houses, especially in combination with relatively cold qanat water. The towers are designed to create a down flow of warm air cooling it while going through brick channels in a house. Sometimes the air is channeled down further through the basement which is linked to the water

level of the qanat, to cool the air extra through the cold water from the mountains. The warm air in the building will rise and leave via a channel on the opposite side in the tower.
Ab-anbars are (half) subterranean water reservoirs where water is cooled using the chilled air from the attached wind tower(s), often also in use as places to draw water (a payab).

2 Romans aqueducts[2]

The Roman Empire is mostly located in dry Mediterranean terrain where it was a real problem to find perennial water sources. The Romans could take the water from rivers (fig 5) and lakes but these were often polluted. Another reason to avoid river water was the frequent water level change in a river, which made it difficult to build an inlet for an aqueduct. The best locations were always springs at an altitude above the destination of an aqueduct, mostly in karst settings.

Aqueducts were known to the Etruscans and Greeks, but were especially favored and technically improved by the Romans. The aqueducts were mainly built for the purpose of providing water to the public baths and the provision of cities with drinking water, but this could also be obtained from wells.

Fig. 5: The start of the aqueduct of Segovia (Spain) should have been a river tap. At right a weir in the river Acebeda, in the front a sluice gate to direct the water via the aqueduct channel to the ancient city of Segovia (photo: Schram).

More than 1500 Roman aqueducts are presently known from the literature (fig. 6) and these show a large number of different types .
A distinction can be made between industrial aqueducts and consumption aqueducts. Industrial aqueducts were mostly built for mining (NW Spain, Wales), to a lesser extent for irrigation (Valencia), for the production of fish-sauce (Baelo Claudia, Almuñecar, Kouass) or for flushing sediments from harbor basins (Caesarea, Israel). Most aqueducts, however, served cities or smaller settlements, and in some cases isolated villas and bathhouses.

[2] Text mainly based on Surmelihindi 2013, 25 - 30

Fig. 6: Distribution of the known aqueducts over the Roman Empire. Within the Romaq-project (www.romaq.org) literature is collected of over 1500 Roman aqueducts (copyright: 2011 Google).

Each aqueduct has a number of characteristic elements such as a spring, the main channel, bridges, tunnels, inverted siphons, basins, and a terminal distribution station, from where water was distributed to different parts of a city, and to different types of users.

Springs were favored as a water source of aqueducts. Obviously, perennial springs with clean water are a great advantage in building a water supply. In some cases, rivers were directly tapped for aqueduct water, either through a weir (Segovia) if the water supply was constant over the year, or by means of dams (Emerita Augusta, Glanum, Toledo). Another option was to tap groundwater close to the surface by a sicker gallery, usually a covered channel with permeable walls though which water could enter the channel (Cologne, Germany; Almuñecar, Spain; Windisch, Switzerland).

The main channel of an aqueduct was rectangular in cross-section, and covered by a vault or slabs. The inside of the channel was made waterproof with a special red-colored cement with roof tile fragments, opus signinum. The channel of the aqueduct was usually buried to protect it from frost and contamination, but sometimes access shafts were built at regular distances to allow cleaning and maintenance.

Since aqueducts operated by gravity, they should have a low, regular slope from source to target. Steep slopes were avoided since the resulting rapid water flow is erosive and could destroy a channel rapidly.

Aqueducts commonly passed along the contour lines of hills. Where needed, or where a channel had to make a long detour, bridges or tunnels were built to shorten the route.

Valleys were crossed by means of aqueduct bridges such as the Pont du Gard, France, in order to avoid damage when the stream was in flood. These bridges could be one, two or three stories high, with the channel passing on top (fig 7). If an aqueduct was to reach high parts of a city that was not on a slope, it was necessary to build the channel on arcades (fig. 8), such as those outside Rome. These arcades could carry the aqueduct in levels, with up to three channels being carried by the same arcade, one on top of the other.

Fig. 7: Inside the aqueduct channel. The floor and walls were covered with watertight plaster. On the ceiling one can see the imprints of the formwork used during the construction. (Aqua Anio Novus, S of the Ponte degli Arcinelli, S of Tivoli, Italy). (photo: Schram).

Fig. 8: The Kirkgoz (40 arches) bridge of the aqueduct of Side (Turkey). Note that the white spots at the foot of the bridge are visitors. (photo: Schram).

Tunnels were usually built by sinking vertical shafts along the trajectory, and connecting them (fig. 9). When the hill or mountain to be crossed was too high, a tunnel was driven from two sides, with obvious difficulty to meet in the middle. This type of deep tunnel could be up to 8 km long (Traconnade, Aix-en-Provence, France). Tunnels were occasionally also built where the geology made a masonry channel vulnerable, for example in areas with soft rock or land sliding.

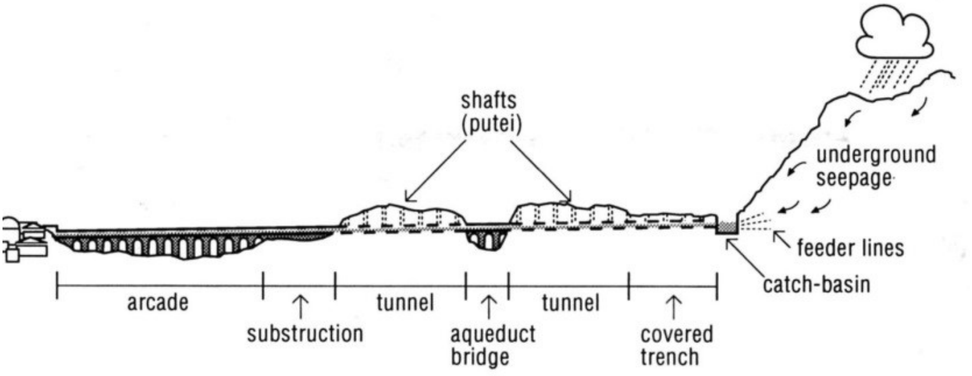

Fig. 9: The basic scheme of an aqueduct with at right the source (a river tap, spring or dam) and at left a basin where the water is distributed among the users. Do realize that 80% of the course of an aqueduct is subterranean and laid in a covered trench. Note the works of art: arcades, tunnels and bridges. (Drawing from: P.J. Aicher (1995): Guide to the aqueducts of ancient Rome).

Where small rock spurs had to be passed, in some cases a trench was preferred: here, the rock mass is cut vertically to a deep enough level to allow the aqueduct channel passage (Fréjus, Cahors, both in France; Chelva, Spain).
If the bridge had to be higher, or the valley was too wide for a stable bridge, another solution was found in the form of an inverted siphon: here, a water pipe was built and laid out on a system of slopes and a low bridge crossing the central valley, known as a venter bridge. Such inverted siphons were constructed by series of lead pipes (Lyon) or rows of perforated blocks (e.g. Aspendos and Patara, both in Turkey).
Basins were built shortly after the source, before bridges in order to capture sediment in the water. Where branches of an aqueduct join, or where they split, basins are usually built to avoid damage by turbulence. In addition, such basins usually have structures to let out water (overflow) or to be able to close off one of the branches.
Where aqueduct channels had to accommodate a large difference in height, special adaptations had to be made. The most common adaptation was the construction of drop shafts, where water can drop down in a well-like part of the aqueduct, to continue at a lower level (Cordoba, Spain; Martigny, France; Cuicul, Algeria; Autun, France). Another solution was the use of ceramic pipes, which are less subject to damage as can be seen in Patara, Turkey.

The final structure in all aqueducts is a basin with structures to subdivide the aqueduct water over several tubes or channels to its final users. This structure is called castellum divisorium. In some cases, such as Pompeii (Italy) and Nîmes (France) (fig. 10), the structure can be very complex, but in most cases it is a simple set of basins and pipes.

Fig. 10: The well-known water distribution basin (*castellum divisorium*) of the aqueduct of Nimes (France). The inlet in the background may have been equipped with a kind of sluice gate. In the front some of the in total 10 openings for (ceramic ?) pipes to distribute water to the users (Photo: Hauke Krebs).

3 The comparison

As stated above, on a superficial view the Persian qanat might be considered as the predecessor of the Roman aqueduct. If one looks into more details, there are indeed some similarities but even a considerable number of differences.

Only a few scholars made a start with a comparison of both water supply systems among which Hodge, Castellani, Kamash and Voudouris .

Hodge first ascertain that, although qanats originated in ancient Iran, some were at least in existence in Roman lands (Hodge 1992, 37-8). He notes that their chief differences were twofold: “Aqueducts were very largely built to serve baths and as an expression of civic pride… Qanats, on the other hand, supplied water needed for subsistence, for life itself”. His second remark in this respect: “Aqueducts were in general built to serve existing towns, often with several centuries of prosperous existence behind them before the arrival of the aqueduct… Qanats, on the other hand, were constructed to deliver their water at whatever point was selected by the surveyor as the most technically suitable, and the village then grew up around it…”

As a consequence of the above, he concludes as follows: “The difference, thus, is that with an aqueduct, the town existed first, while with a qanat, the qanat did.” Braun cites Hedin (Hedin 1910): “Gewöhnlich geht es wohl so zu, dass ein neu angelegter Qanat Veranlassung zur Entstehung eines Dorfes gibt, nicht umgekehrt.” [Usually a new built qanat leads to the birth of a village, not the reverse.] (Braun 1974, 15).
Castellani states that aqueducts - contrary to qanats - do not tap groundwater but only transport water, whether from a spring or river (Castellani 2001, 25 - 32). During construction of an aqueduct shafts are also used. However, the construction of qanats typically requires the use of a single digger that progressively works back to the mother well, while the construction of an aqueduct can be arranged with different teams at the same time resulting in huge savings in execution time.
Kamash, referring to Ron (Ron 1989, 231-234), notes two major differences between a qanat and a spring flow tunnel, one of the possible starts of an aqueduct: “The origin of a qanat is a [subterranean wds] well that is turned into an artificial spring. In contrast, the origin of a spring flow tunnel is the development of a ‘real’ [super terranean wds] spring to renew or increase flow following an episode of the water table receding”. Secondly “… shafts, which are essential to qanats, are not essential to spring flow tunnels” (Kamash 2006, 92).
Voudouris only compares the definitions of both aqueduct and qanat / karez which leads him to the conclusion that qanat is identical to aqueduct, or at least is included therein. “This should be clarified by establishment of various categories of aqueducts” (Voudouris 2013, 1341).
In the following table we make our own, broader comparison where we grouped 17 basic elements of both qanats and aqueducts under three headings: Physical Geography, Technology, and Societal.

Table 1a: Comparison of Persian Qanat and Roman aqueduct (basics).

Element	Persian qanat	Roman aqueduct	Remarks
Numbers	33.000 (in Iran 2001)	1.400 (in total)	In general: Motiee 2006; Romaq (see: http://www.romaq.org/) Details in: Cenesta 2003, 37; Cressey 1958, 37; English 1968, 170, 171; Beaumont 1971, 42 – 50; Khan 1995, 92; Lightfoot 2009, 11, 20; Bonine 1982, 145
Cross-section	0,6 x 0,9m	0,6 x 0,9 m	
Typical length	20 km	20 km	
Typical discharge	2.000 m3/d	20.000 m3/d	
Typical depth	10 - 50m	5m	
Typical fall	0,07 - 0,1 %	0,1 - 0,5 %	

Table 1b: Comparison of Persian Qanat and Roman aqueduct (aspects of physical geography).

Element	Persian qanat	Roman aqueduct	Remarks
Character of the terrain	Alluvial fans in mountainous area's	From mountainous to almost flat area's	Cressey 1958, 28, 30; English 1968, 170; Humlum 1965, 116/1684; Wulff 1968, 94, 96; Beaumont 1971, 39, 41; Braun 1974, 113; Weingarten 2007, A1555-6; Khan 1995, 91; Lightfoot 2009, 4; Ahmadi 2010, 126
Climate	Mainly in arid regions	Semi-arid and wet area's	Cenesta 2003, 6; Beaumont 1971, 41; Braun 1974, 113; Motiee 2006,577; Lightfoot 2009, 19 (+ opposite?); Bonine 1982, 145; Ahmadi 2010, 126
Source	Mother well(s) in an aquifer	Spring. river, lake; by exception well or aquifer	Cressey 1958, 30; English 1968, 172; Humlum 1965, 116/1684; Wulff 1968, 96; Beaumont 1971, 39; Motiee 2006, 575; Ahmadi 2010, 126
Type of source	Delayed delivery	Instant delivery (spring, river)	Goblot 1979, 26
Place in the landscape	100% subterranean	Some 20% above surface	Cressey 1958, 36; Humlum 1965, 116/1684

Table 1c: Comparison of Persian Qanat and Roman aqueduct (technological aspects).

Element	Persian qanat	Roman aqueduct	Remarks
Builders	Paid specialists, professionals	Slave specialists, contractors, sometimes military personnel	Cenesta 2003, 13; Cressey 1958, 29; English 1968, 171, not 178; Wulff 1968; Beaumont 1971, 39; Braun 1974, 113; Khan 1995, 91; Lightfoot 2009, 9, 13; Bonine 1982, 145; Ahmadi 2010, 128, 129
Course	(Almost) straight line	Sinuous, following the contour lines	Khan 1995, 92; Lightfoot 2009, 11 [see the many aerial photographs]
Works of Art	No, by exception subterranean dams and mills; chilled water used for cooling	Bridges, tunnels, arcades, siphons, distribution stations	Cenesta 2003, 7, 8 ; Cressey 1958, 29 ; Ghornabi 2007, 168-170 ; Mostafaeipour 2010 ,75-77; Yazdani 2006, 434 – 437; Lightfoot 2009, 17; Bonine 1982, 148, 155; Ahmadi 2010, 133
Distribution	Sluice gates, open channels; timesharing; use of clepsydra, sundial, stars	Castellae divisoria plus lead or ceramic pipes	Cressey 1958, 38; Wulff 1968, 100; Cenesta 2003, 14, 16, 17, 38; Mostafaeipour 2010, 76; Khan 1995, 92, 94; Bonine 1982, 148-151, 153
Storage	Only local, in modest volumes	No, only behind some large bath houses in Rome	Cressey 1958, 38; Cenesta 2003, 7; Mostafaeipour 2010, 76; Motiee 2006, 578; Bonine 1982, 154, 156
Surplus water	Wasted or reused in other qanats at lower level	Flushing sewers and public toilets, fullers	Cressey 1958, 37; Beaumont 1971, 39, 40; Bonine 1982, 158

Table 1d: Comparison of Persian Qanat and Roman aqueduct (societal aspects).

Element	Persian qanat	Roman aqueduct	Remarks
Users	Irrigation and public. By exception (for cooling) in private housing	Public and bathhouses. But also to some degree industry, private individuals, farmers	Cenesta 2003, 7;English 1968, 170; Motiee 2006, 576; Lightfoot 2009, 6, 21; Bonine 1982, 145
Ownership	In cooperation (10 - 250 stakeholders / farmers). Sometimes rich individual / landlord	Public body, town council	Cenesta 2003, 8, 13, 14, 31; Cressey 1958, 37; English 1968, 178(neg), 179; Humlum 1965, 117/1685; Wulff 1968, 100 (neg); Braun 1974, 113; Mostafaeipour 2010, 73; Khan 1995, 94, 96; Lightfoot 2009, 21; Ahmadi 2010, 131
Finance	Members of the cooperation (by exception a private investor)	Local Maecenas, emperor, town council	Cenesta 2003, 15
Status within society	The only water source, essential for life, utilitarian	Additional to existing water sources, luxery (baths, nymphaea), showcase of pride and power	Cenesta 2003, 7; Cressey 1958, 27, 29, 38; English 1968, 170, 175; Braun 1974, 113; Motiee 2006, 578 Lightfoot 2009, 27
Present status	Many still in use	Almost all out of use; some reconstructed	Cenesta 2003, 29; English 1968, 174; Wulff 1968, 94; Khan 1995, 92, 98; Lighfoot 2009, 9, 25

4 Some remarks additional to the table

Most qanats can be found in mountainous areas and on plateaus. The difference between these conditions results in distinct mean lengths of the qanats and of the mean depths of the mother wells. In mountainous areas the qanats are smaller, have a seasonal discharge and are constructed in alluvial deposits (Lightfoot n.d.,3; Ahmadi 2010,131). In these area's the precipitation is very modest, between 100 and 300 mm annually, although some qanats can be found in more humid environments. In Iran the mean is 275 mm/y of which more than half of it falls along the south coast of the Caspian Sea.

The heart of a qanat is the mother well in an aquifer. Because a qanat has a water source of its own, it makes it special and distinct from an aqueduct which is - in principle - only a conveyance system. A qanat is an integrated system of subterranean water collection and water transportation, although in the literature sometimes reference is made to a spring qanat that draws its water from a natural spring, or a wadi qanat, diverting a water stream (Wessels 2008, 93; Al-Ghafri 2012, 200-201).

In principle a qanat channel is 100% subterranean and comes to light in a command area where its water is tapped for domestic and agricultural purposes.

For details about the construction process of a qanat, see: English 1968,171; Ahmadi 2010, 128 and Semsar Yazdi 2012,122. The workers are often referred to as moghanee or moqani but each heads a small group of 3 - 5 coworkers with distinct tasks (Cenesta 2003, 13). The moqani are very specialist people. The most famous ones came from Iran and were even active in North Iraq and Baluchistan (Lightfoot 2009, 10; Khan 1995). Along the longer qanats subterranean dwellings - bookans - were built as living quarters and shelters at almost every 3 km. These 'houses' lost their function, now good means of transportation are available (Semsar Yazdi 2012, 135).

In general a qanat follows a straight line from the mother well to the command area, apart from a necessary bypass because of a cave in or an impenetrable rock formation. Although not often expressed in the qanat literature (Khan 1995, 92; Lightfoot 2009, 11), the straight course of a qanat is easy visible on aerial photographs.

There are not many works of art associated with qanats. Among the most famous ones are the subterranean, pierced dams in the Vazvan region, 100 km NW of Isfahan (B 2007, 168; Semsar Yazdi 2012, 99), and near Jandagh, 375 km NE of Isfahan (Salih2006, 83) which perforations could be closed and opened little by little by means of plugs. Special attention should be given to the qanat bridge of Khanaraq (Bonine 1982, 155).

Another striking example of engineering is the double Moon qanat in Zavareh, Ardestan, based on two separate mother wells in two aquifers but using common shafts (Ahmadi 2010, 132; Semsar Yazdi 2012, 97). Qanat water has some special applications in Iran: it has been used for grinding grain (Bonine 1982, 148; Lightfoot 2009, 17), sometimes in subterranean setting (!). Another application is cooling private houses and offices, often supported by wind catchers (Bahadori 1978, 149; Ahmadi 2010, 133). The same physical laws apply to water and even ice storage, collected in winters and cooled by wind catchers and doomed roofs with (a) ventilation aperture(s) (Bahadori 1978, 152; Boustani 2009, 507).

The technicalities of the distribution of qanat water by means of wooden frames and sluices do not get much attention in the literature. Seldom reference is made of mud dams, wooden and metal gates, ponds, water meters and dividers (Braun 1974, 63, 84, 85, fig 24, 32 - 34; Bonine 1982, 153 - 155). On the other hand information about the social and managerial aspects of water and land distribution is overwhelming (Bonine 1982, 148-157; Cenesta 2003, 12 - 16, 93 - 97; Wessels 2008). Striking is the use of the 'clepsydra' (a time measuring device), the sundial, and by night the stars for time measurement (Bonine 1982, 150 - 151) necessary for time-sharing scheme's.

As far as water storage takes place, two methods are in use. Generally speaking the daily water demand is not in pace with the constant supply which makes it necessary to store water in ponds or reservoirs; selective opening of the pond gate will result in a greater water volume in the channels and less water loss. This method is especially productive along qanats with modest and small capacity (Bonine 1982, 154). To cope with seasonal fluctuations in the supply, large reservoirs can give some relieve. More drastic measures were taken in Vazvan (Iran) using a subterranean dam with apertures at the start of the dry zone of the qanat: a kind of underground reservoir close to the aquifer to store water in the winter for use in the grow season (Cenesta 2003, 7).

In areas of a mean precipitation of less than 500 mm annually, little water will be wasted: every drop counts. Surplus water - if any - is stored where possible, otherwise made available for qanats at a lower level.

In almost all areas with qanats, the use of water is free of charge for the public and animals (Mostafaeipour 2010, 73). The public simply taps qanat water with a bucket at a pond or channel and where a channel several meters below street level is situated, access it via a special facility with stairs, called a payab (Semsar Yazdi 2012, 92, 133). Other users are the mosques (for washing hands and ritual ablution), forts, public baths, and households (washing dishes and cloths). But many rural qanats find their origin in irrigation.

Although wealthy farmers built their own qanats, the majority were ordered and owned by the local community / tribe in a shareholder system. Generally speaking: a qanat is a community enterprise (Khan 1995, 96). There is not a direct relation between water rights and landownership although a certain balance must be present. Both land and water rights were rented or sold. Bigger qanats may have 25 - 250 shareholders, so some management, record keeping and dispute settlement is necessary. Maintenance is essential and expensive, so many types of financial transactions - in kind, money or rights - are involved (Bonine 1982, 157).

As Braun stated in 1974: “Until recently qanat irrigation was one of the foundations of Persian agriculture” (Braun 1974, 113). Hodge, as cited above: “Qanats … supplied water needed for subsistence, for life itself” (Hodge 1992/2000, 38). Before the introduction of the pump well, the qanat was the only water source in many villages, so no qanat meant water nor food.

Even quite recently (the 70’s) new qanats were built, not only as a result of a rehabilitation schedule. Near Turbat (Baluchistan, S Pakistan) a new system of 5 km was completed in 1976 (Khan 1995, 92).

But from nearly no qanat we know its date of origin; they are often indicated as ‘very old’. Circumstantial evidence sometimes hints on construction in a certain period. So we are talking about water delivery systems of uneven dates: on the one hand qanats from 800 BCE till quite recently and quite a few are still active; on the other hand Roman aqueducts stem from 300 BCE till 500 CE of which only a few are still active after full rework.

5 Qanat or Aqueduct, an example

Let us take an arbitrary example: Hadrian's aqueduct in Athens. What do we know about it - my main source of information is the PhD-thesis of Shawna Leigh (Leigh, 1998).

The Hadrian's aqueduct in Athens is of totally subterranean nature, about 20 km long, with over 400 shafts, 2 to 30 m deep. It was built between 125 and 140 CE and Hadrian financed the construction. The aqueduct was fed by water from the Parnitha mountains in the north, tapped from a large underground spring in an aquifer. During its course many tributaries from subterranean galleries, added extra water. Its course is indicated on the map (fig. 11, nrs. 5-7). The final destination was the reservoir at the foot of the Lykabettos hill. It is uncertain where the water went to, only a few lead and some ceramic pipes have been found which could be related to this 2nd cent. CE water supply system. Some options:

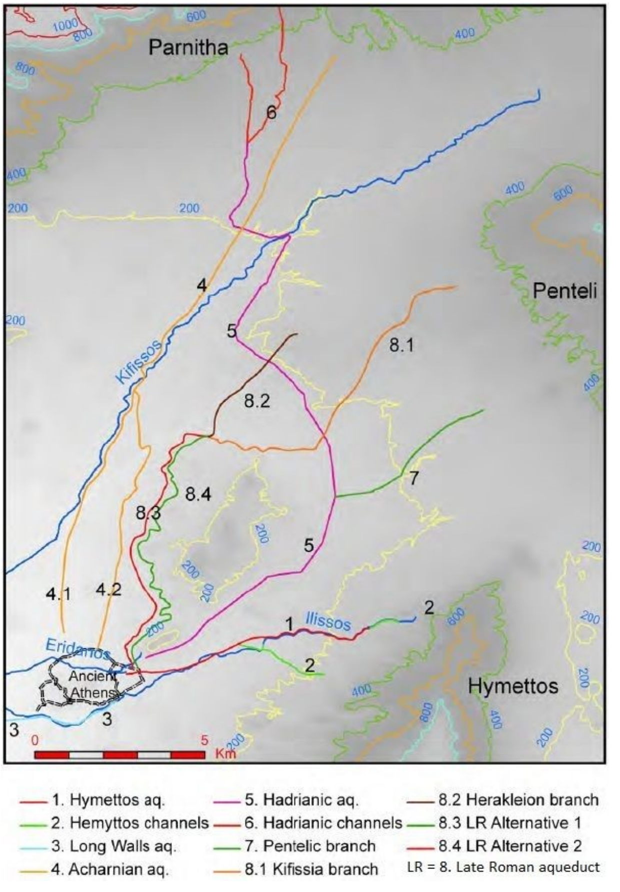

Fig. 11: An overview of the known and surmised aqueducts of Athens (Greece). The violet line nr 5 represents Hadrian's aqueduct from its source in the Parnitha mountains to the Lycabettos reservoir in uptown Athens. (Drawing from Chiotis 2012).

- The bathhouse north of the Olympeion
- The nymphaeum in the south-east Agora
- The Roman bath house south-west of the Agora

There is some evidence that there was an "officer [an epimelete, the author] in charge of the fountains" in Athens who might have been responsible for the whole water supply in Athens, perhaps comparable to the Curator Aquarum in Rome.

Now we come to the main question: was this work of Hadrian, complete subterranean in a semi-arid environment, a qanat? When we apply the major elements of our scheme to this aqueduct, we come to the following overview (table 2).

We can question why the channel was not laid in a straight line. I think it had to do with topographical, physical, morphological, and geological factors but that does not change to whole picture.

Based on the scheme above, the conclusion about Hadrian's water supply system is that it had some elements in common with a typical qanat (it was aquifer fed and complete subterranean f.e.), but it was not a qanat but an aqueduct.

Table 2: comparison of Hadrian´s aqueduct with element of qanat technique

Elements	As with qanats	Hadrian´s aqueduct	Remarks
Source	Aquifer(s)	+	
Course	Straight	-	See the map
Users	Farmers / General public	-/+	In fact: public and bath houses
Ownership	Cooperation	-	City council
Status	The only source of water	-	Additionally to local wells and springs

6 Main conclusions

Based on the main table 1 (a - d) we come to the following conclusions:

- The water source - the aquifer - is an integrated element of a qanat while an aqueduct is only a water transportation system attached to an external water source, often of quite different type (spring, river, dam etc)
- Given its subterranean nature, the course of a qanat is often straight, where an aqueduct - following the contour lines in the landscape - has a quite sinuous course
- Both qanats and aqueducts serve the general public, but much qanat water is used for irrigation where much aqueduct water was used in bathhouses
- Qanats are in principle community based water supply systems financed and owned by a cooperation of users; aqueducts were often paid by a the emperor and/or a maecenas and owned by a public body
- Although the number of active qanats are rapidly decreasing, quite a few are still in use. Only some aqueducts are reconstructed and/or got a second life, often serving agriculture.

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