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From Cut-in to Qanats - Ancient Groundwater Extraction Techniques

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ABSTRACT

Where a hillside stratified aquifer intersects the earth surface, springs and seepings from the surface are observed. Cutting into this zone, thus opening it by digging, allows to increase and capture water outflow. As a matter of principle this classical method for water extraction without pumping, which is still found in hilly rural regions today, was already used 3600 years ago by the Hittites to fill the ponds of their capital Hattuşa in Central Anatolia. The today sedimented reservoirs were dug downhill of groundwater bearing zones. Rising in winter, groundwater discharged into the ponds through alongside cuts. The Hittites avoided the risks of strongly varying surface flows by opening near-surface groundwater and stratum aquifers. Although hydraulic investigation based on in-situ measurement of groundwater level supports the short-term efficiency of the ponds in supplying water to the ancient city, at the long-term, the decline of the Empire was probably triggered by severe droughts expanded over years. This seems plausible as severe droughts are still being experienced. For a higher and more reliable water yield, the further development went from 'cutting' in to 'penetrating' into the aquifer with tunnel-like drain conduits which collected the water and conveyed it to settlements and irrigation schemes. The improved water extraction system, named qanats, appeared in Eastern Anatolia and Persia about 500 years after the abandon of Hattuşa. An example of a qanat system in western Iran is presented in this study with less emphasis compared to the cut-in yet representative enough to demonstrate its role in supplying water sustainably. We conclude that the ancient time thinking is the same as that of modern engineering, and the ancient time hydraulic works are fundamental for today's civil structures.

Keywords: Cut-in, qanats, groundwater extraction, Hattuşa, Hittites, Persians.

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1. INTRODUCTION

With increasing concern on the global climate change and the local asymmetrical balance between water demand and supply, drought remained one of the unsolved problems of hydrological extremes [1]. This is the fundamental reason for the bloomed interest about the drought not only to better understand its technical context at local, regional or larger scales, and to develop methodologies [2-6] but also to link the drought with its social aspects due to the direct impact on economy, ecology and society [7-8]. As it is for today, the drought has affected on the society in the ancient time. Its effect has been such strong that several well-known civilizations including the Mayas [9-11], the Hittites [12-13], and civilizations along the ancient Silk Road [14] have collapsed because of its consequences reducing the agricultural yield, causing famine and destabilizing the food security.

Drought is related to deficit in water resources through a cause-effect link. Any deficit in water makes the resources unsustainable and thus unreliable. To combat water deficit as a result of unsustainable water availability because of either the usual within-year seasonality or the over-year variability during prolonged dry periods with severe droughts, water is collected in natural or human-made small scale ponds or large-scale dam reservoirs. This has been practiced in the ancient time as well in a much less modern fashion than today. The Hittites, an ancient civilization in Central Anatolia, Turkey, have practiced these by building dam to collect water in reservoirs. A simpler technology they have practiced is the so-called ‘cut-in’ the groundwater aquifer, which is the issue we present in this study. In the absence of modern machinery technology in the ancient time, stored water has been conveyed to lower altitude points where water is demanded by using the gravity through open channels or underground pipes. For arid regions where surface water resources are lacking, qanats, another technology, that convey water from the groundwater aquifer through underground galleries excavated for long distances have been used.

In this study, we look at these two ancient water extraction techniques; the ‘cut-in’ and ‘qanats’, the latter is being more engineered than the former. The ‘qanat’ technology has been well documented in the literature, while the ‘cut-in’ technology itself and its transition (or better we say its evolution) from the water-storing ‘cut-in’ to the water-conveying ‘qanats’ has not been well demonstrated. Thus, we pay an attention to this evolution with less emphasis on qanats through examples from Central Anatolia in Turkey and Western Iran.

2. THE HITTITE’S CUT-IN WATER COLLECTION SYSTEM

Among many ancient civilizations, the Hittites who settled in the Hattuşa (Hattusha) region in Central Anatolia, Turkey (Figure 1) have left remarkable remains of water works [15]. Hattuşa is in the western part of the Kızılırmak River basin at approximately 40°N and 34.6°E. The area of the ruined city rises from about 950 m above sea level in the north to 1250 m in the south. The mean annual temperature is between 8 and 9°C, with great seasonal variation. Mean annual precipitation is around 500 mm, significantly smaller than the potential annual evapotranspiration of about 1000 mm caused by the high solar radiation. The deficit of 500 mm occurs in the period from April to November and leads to high water losses and intermitting the surface runoff. The discharge of the small creek, Budaközü, which flows in the valley east below the ruined city to the north, fluctuates at the gauging station 15-166 Boğazkale of State Hydraulic Works (Devlet Su İşleri) of Turkey between more than

25 m^3/s (400 $l\ s^{-1}\ km^{-2}$) at snow melting season and less than 20 l/s (0.32 $l\ s^{-1}\ km^{-2}$) in the dry summer.

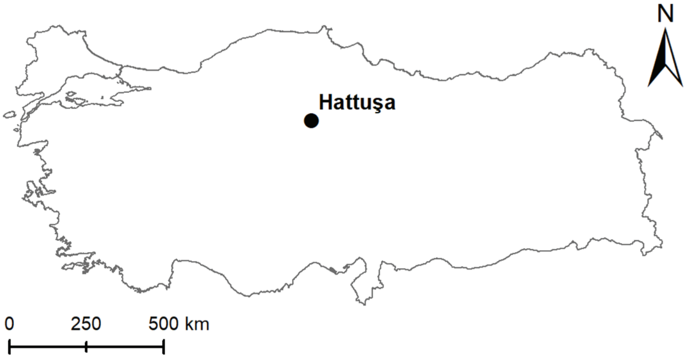


Figure 1 - Location of the Hittites' capital city Hattuşa (Hattusha) in Central Anatolia, Turkey.

The excavations and investigations in the archaeological site yielded extensive knowledge about construction techniques, history, culture and social structure of the Hittites and life in their capital Hattuşa (Figure 2). However, the issue of the city water supply received less attention, apart from the discovery of some cisterns, water basins and springs. There are remains of dams, irrigation canals, and water collection structures from the Hittite period in Central Anatolia dating back to the second millennium BC [16]. Many thousands of people lived and worked on the steeply sloping terrain of today's ruined city, whose households, gardens, livestock, workshops, and places of worship had to be supplied with water and protected from fire. Targeted water management was necessary for this, especially in view of the hot and dry summers.

In 1989, larger, completely sedimented water reservoirs were discovered in the upper city and excavations were carried out on them, initially at the two eastern ponds with a capacity of approximately 36,000 m^3, and from the year 2000 at the complex of the five southern ponds (total volume 20,000 m^3) (see map in Figure 3 from [17]). When P. Neve uncovered East Pond 1 (Ostteich 1), found by himself, he considered it to be a cultic facility, a "sacred pond". However, the size of the reservoir and several Hittite hydraulic structures that were documented in the following period suggested that the ponds played an essential role in the water supply. Therefore, the issue was investigated from the hydraulic engineering perspective [18].

In the region, numerous artesian wells and cattle troughs indicate abundant groundwater resources while at the same time, rivers and streams fall dry. There are also various spring horizons on the slope of the ruined city and south of it, which presumably fed the ponds 1 and 2 in the central upper town (Figure 3), as well as some fountains in the urban area. In modern times, the city of Boğazkale, located directly to the north below Hattuşa, is supplied with drinking water from the hillside springs, some of which are located within the ruins. The wells are still in use today.

Figure 2 - Remains and ruins of the lower city of Hattuşa.

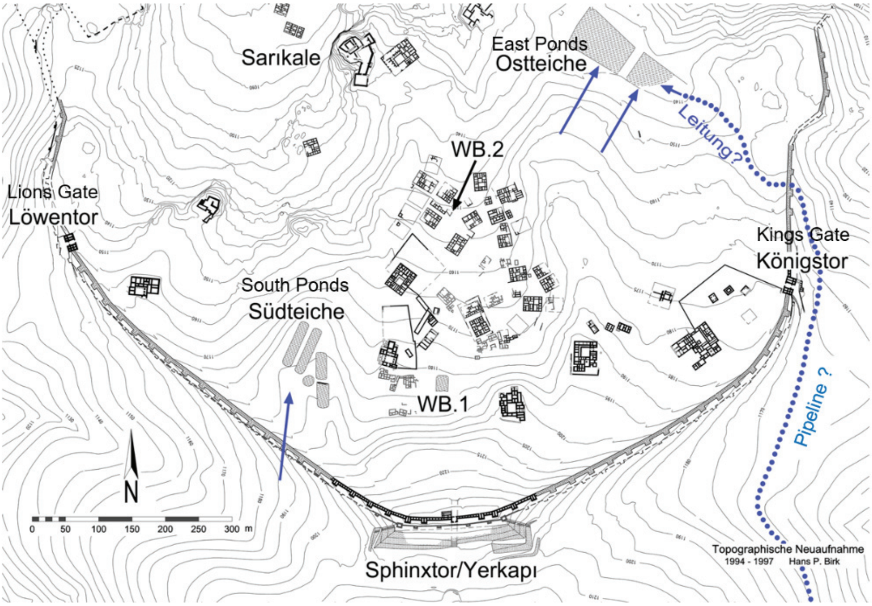


Figure 3 - Topographic map of the upper city of Hattuşa with East and South ponds [17] as revised by J. Seeher in 2023. The blue dotted line with question marks shows the approximate routing of the initially assumed pipeline, the blue arrows indicate the seepage directions of groundwater into the ponds.

3. FROM CUT-IN TO QANATS

We easily understand that after the climatic catastrophe and its impacts on civilization, antique engineers looked for methods for a higher and more reliable water supply. After the 'cutting-in' water-bearing layers, it was logical to expect more water by 'penetrating' the layer through a gallery called qanats (from Arabic canal) as a follow-up technology. Qanat systems were operating 500 years later in Eastern Anatolia [19] and then or simultaneously in Persia for which an example from western Iran is given in this study. It is likely that the new technology spread from the then empire of Urartu. Some scholars report that the qanat technology might have been developed independently in various regions of the Middle East, Mediterranean and North Africa [20]. However, it is generally agreed that qanats were developed somewhere between the northwest of today's Iran, southern Azerbaijan and Armenia, and eastern Turkey [21], and spread to the Mediterranean, North Africa and Europe through cultural exchange, conquests, resettlement, migration and wars; to South America through colonization; and to Afghanistan, Pakistan, China and Japan through trade routes, particularly the Silk Road [22-25]. For China, while one theory says that the shaft/tunnel construction technology was used by ancient Chinese, thus it was a local innovation developed by indigenous people, it is more convincing that this technology was imported to China along the ancient Silk Road [26].

Despite the uncertainties about the time and place of the origin, it is mostly agreed that settlements as old as of 1000 BC relied on the qanat system for irrigation, meaning that the qanat technology is at least 3000 years old [27]. Some discoveries in central Iran date even back to 2000~3000 BC; e.g., the Gonabad qanat system in Iran of 2700 BC is recognized as the oldest in the World, still used for irrigation of Saffron farmlands [28]. Many existing qanat systems have stopped flowing by the effect of droughts as in the example from Afghanistan [29] while some may, at the same time, be flooded after the human-made intervention as in the example from the Bouda Oasis in Algeria [30]. With the rise in the awareness and demand for sustainable development and resilience against the nowadays climate change, the ancient-time qanat technology gained popularity among the modern-time researchers and practitioners. Among many, for instance, the ancient qanat systems in Iran [31], Syria [32], Cyprus [33], Algeria [34], China [35], and Afghanistan [36] were studied.

We see that qanats are mostly built where there is no permanent and reliable surface water available. When surface water resources are scarce or groundwater is preferred as the main water resource, qanats could particularly be useful. They prevent evaporation from water flowing under the surface without being in direct contact with the heat. Thus, they were practiced mostly in arid and semi-arid parts of the Earth where one of the sustainable water resources is groundwater. It should also be emphasized that the qanat system is not simply a set of vertical wells connected to a sloping conduit. It is made of a complex networks of water distribution with connections between qanats to ensure water supply to each owner [37].

4. RESEARCH HYPOTHESIS

In a first stage of the field inspection and sighting of documents, the earlier assumption of adduction of water through pipes or canals from outside the city of Hattuşa (hypothetical route dotted in Figure 3) could be practically ruled out due to water management, strategic and topographical considerations, especially since no remains of such a pipeline were found. In contrast, the perennial pasture fountains on the slope (Figure 4) indicate layers carrying groundwater. Figure 5 shows a schematic section in south-north direction through the area of the ruined city and the eastern ponds, considering the topographical and hydrogeological conditions. Geologically, the area is characterized by ophiolitic series. The percolating precipitation is dammed up on impermeable or low permeable layers of serpentine, loam, or clay. The resulting groundwater drains down on these layers and emerges through springs or wells situated where the impermeable layer meets the ground surface.

Figure 4 - Pasture fountain on the slope.

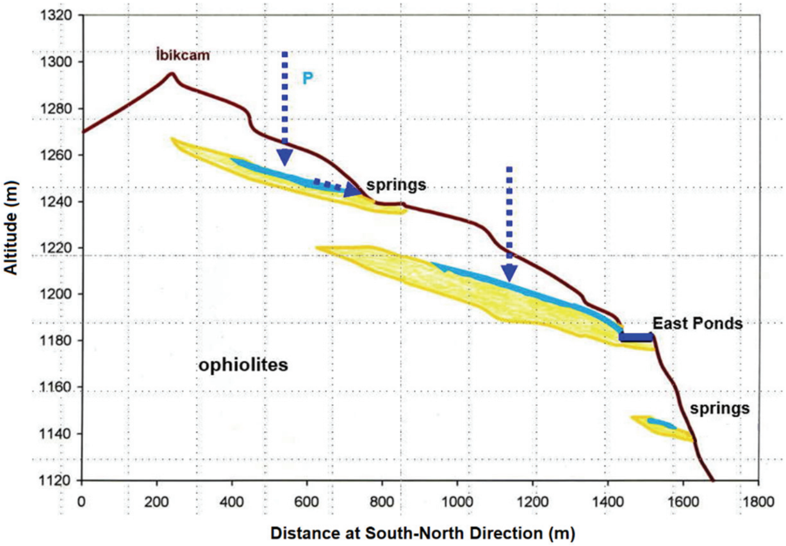


Figure 5 - Schematic topographical and geological section of the East Ponds. Infiltrating precipitation is retained and distributed by impermeable clay layers feeding springs.

The following hypothesis was defined: As the nowadays herders who build simple troughs at out seeping spots for their animals, the Hittite engineers were aware of the water bearing layer (Figure 5). Instead by a spot opening, however, they opened it by a longer cut for a higher yield. A reservoir (pond) dug into the impermeable layer below the cut collected and stored the discharging groundwater.

5. HYDRAULICS AND HYDROLOGY

5.1. Characteristics of Rockfill Dam and Principal Mechanism of Filling the Ponds - Hydraulics

On the valley side, the eastern ponds were enclosed by approximately 1.5 m high rockfill dam, which, like modern rockfill dams, were equipped with a sealing core made of clay with a foundation in a spur ditch (Figure 6). The mountain-side southern bank of the pond was also sealed. Figure 6 shows a cross-section through the spur ditch that was deepened into the impermeable layer and filled with clay. Remains of an overflow channel can also be seen in the archaeological site. This was apparently a spillway, an indispensable structure even on today's dams. With a usable volume of approximately 24,000 m^3 the East Ponds could support thousands of inhabitants and store essential volumes for firefighting, livestock watering, gardens, crafts and ritual purposes.

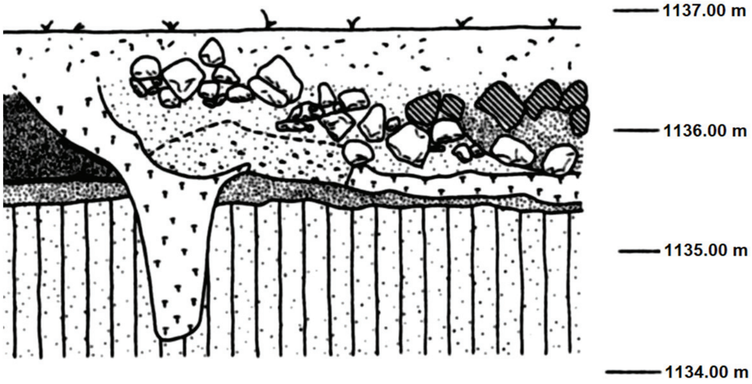


Figure 6 - Cross-section of the rockfill dam through the spur ditch [38].

Following the idea in the hypothesis, in autumn 2009, boreholes were sunk directly above the ponds in the Hattuşa archaeological site and groundwater level measuring points were set up to collect data. The recordings of the groundwater level confirmed the working hypothesis. In the wetter winter half of the year, the groundwater rises and pours out of the cuts into the ponds. For this purpose, the groundwater level had to exceed a minimum height (threshold level), which required sufficient precipitation for the formation of new groundwater. Figure 7 shows the weekly measured groundwater level from 2009 to 2011 and the replenishment processes at the hillside edge of East Pond 1. In these years with normal annual precipitation, the threshold groundwater level was exceeded for many weeks allowing that the ponds would have been filled sustainably.

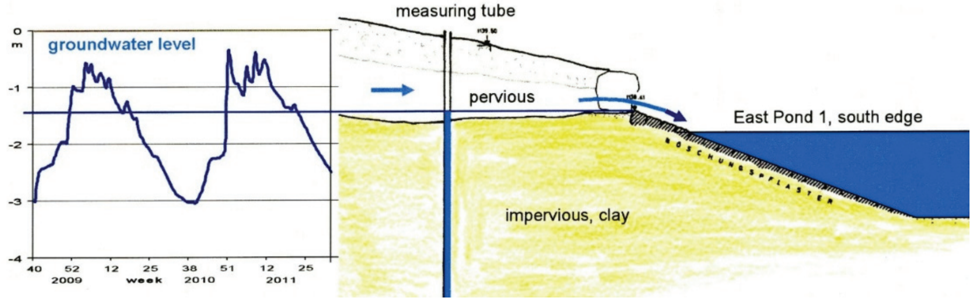


Figure 7 - Measured groundwater level in 2009 – 2011 (left), East Pond 1 and inflow principle (right)

5.2. Temporal Variation - Hydrology

While the hypothesis and the principal mechanisms of filling the ponds of Hattusa by cutting in groundwater bearing hillsides are confirmed by the measurements, the quantification and determination of the temporal distribution of these inflows need further evaluations. In the following, a hydrogeological approach is proposed which is based on the performed drillings as well as some assumptions and estimations. It is explained how the ponds are filled based on in-situ measurements of groundwater level.

The approach is applied for the example of East Pond 1 (Ostteich 1). Available topographical maps (e.g., Figure 3) show that the land surface slopes by about 10% from the south towards the southern cut edge of the pond where the filling was to be expected (Figure 7). The same slope is assumed for the approaching groundwater surface; several smaller seeps and wells are backing this assumption. Particularly valuable for the method was the existence of a modern well in the vicinity uphill of the East ponds. This perennial fountain named Kör Ahmet Pınarı (Blind Ahmet Spring) has a trough for livestock watering and is fed via a perforated tube from the same aquifer as the East Ponds were. In addition to the groundwater levels at the installed measuring tubes at the ponds, the outflow of the fountain was measured every week since September 2009 by counting the seconds to fill a 10-liter bucket.

When in winter due to precipitation, the groundwater rose above the threshold level, the inflow to the pond came out of the same subsurface reservoir as the fountain outflow. In a simplified view, during each time step of 7 days, a water volume with a rectangular cross section of about 90 m length (length of the cut-in, thus the southern edge of the pond) and its measured height of groundwater level minus threshold height is passing the cut-in. The reservoir consists of pervious material (see Figure 7), gravel, sand silt etc. for which a hydraulic conductivity of $k_f \approx 1 \times 10^{-3}$ m/s was assumed. The percentage of effective pore volume (n_{eff}) of the total volume can be estimated by [39]

$$n_{eff} = 0.462 + 0.045 \ln(k_f) \qquad (1)$$

Thus, in the present case, $n_{eff} = 15\%$. Following the slope, the water stored in the pores will move towards the pond. Since groundwater flow is considered as laminar, the Darcy equation can be used to estimate flow velocity (v_f):

$$v_f = k_f\, I \tag{2}$$

where I is slope of the groundwater surface. For $I = 0.1$ and $k_f = 0.001$ m/s, $v_f = 0.0001$ m/s is obtained. With this velocity, groundwater of a flow travel length $f_t \approx 60$ m flows out at the cut-in line during one time step of 7 days. At a height above the threshold (e.g. $h = 0.5$ m), a water volume of about 400 m^3, typically observed at 20 measurements in a year (weeks of groundwater level above threshold), a volume of around 8000 m^3 would pour out into the pond. With a basis area of 90 m x 50 m = 4500 m^2, this would correspond to a filling depth of 1.8 m in the pond.

However, it is important to consider that the inflows into the pond are not directly represented by the measured groundwater levels above the threshold. These values indicate the grade of filling of the aquifer or the recharge of this reservoir. The outflows of groundwater storage ($Q_{storage}$) above the threshold (1.5 m) determined as lined out above are the inflows into the pond. Since the flows into the pond are originating of the same aquifer as those of the nearby fountain, it is expected that their temporal pattern, their response to the variation of groundwater levels will be very similar, except the volumes.

For verification, we applied the linear reservoir algorithm to calculate inflow (Q_i) and outflow (Q_o). The linear reservoir algorithm assumes that at any time the outflow Q_o is proportional to storage volume S, thus:

$$S = kQ_o \tag{3}$$

The flow recession is described by an exponential equation. Since the algorithm corresponds to the Darcy law (laminar flow), its application on groundwater processes is reasonable. Continuity equation is:

$$S_t = S_{t-1} + (\overline{Qi} - \overline{Qo})\Delta t \tag{4}$$

in which $\overline{Qi}$ and $\overline{Qo}$ are inflow and outflow discharges, respectively, averaged over time interval Δt. Equation 4 can be numerically solved to compute outflow at the current time by using outflow at the previous time and inflows at the current and previous time steps, as:

$$Qo,t = \frac{(Qi_t + Qi_{t-1})\; 0.5\,\Delta t + Qo_{t-1}\,(k - 0.5\,\Delta t)}{k + 0.5\,\Delta t} \tag{5}$$

The calibration of the recession coefficient k which has the dimension of time is based on the recession curve analysis; k is the reciprocal value of the slope of the logarithmic recession curves. Figure 8 shows the calibration using the recession of the fountain flows from 31 May to 5 October 2012. As the slope is 0.0503, the reciprocal is 1/0.0503 ≈ 20 and with weekly (7-day) time interval of the measurements, k becomes 140 days.

The computed outflows of the aquifer and inflows into the pond are shown in Figure 9 together with the fountain outflow. For an easier visual comparison, the fountain outflow was extrapolated to $Q_{storage}$ at East Pond 1 from 2010 to 2015, by multiplying with the ratio between the volumes of groundwater storage and the fountain, $\mathrm{Vol}_{storage}/\ \mathrm{Vol}_{fountain}$, for every year. Figure 9 shows also the time series of groundwater storage ($Q_{storage}$). The inflow volumes and their temporal patterns are now clearly seen. It shows the retention effect and the characteristics of flows having passed a reservoir: attenuation of flows, retardation, with the typical indication that the peak of the outflow hydrograph is positioned on the recession limb of inflow. The coefficient of determination between $Q_{fountain}$ and the computed outflow into the pond $Q_{reservoir}$ is $R^2 = 0.9$.

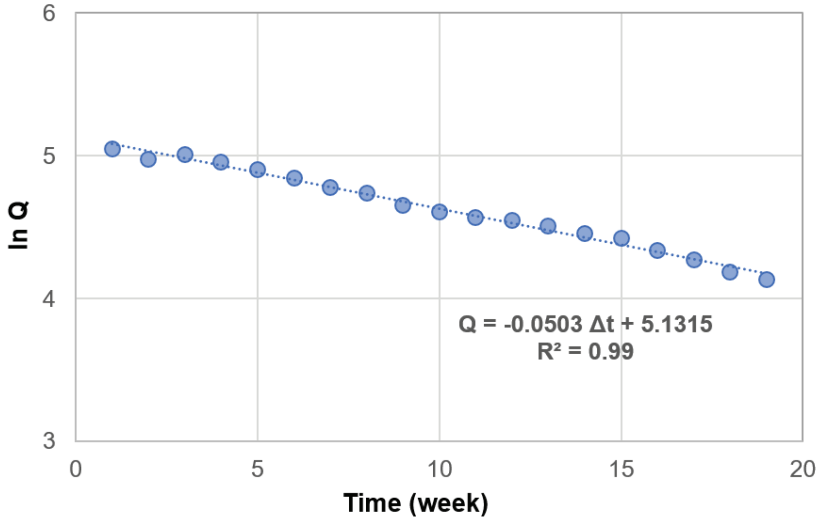


Figure 8 - Calibration of recession constant k for the fountain flow ($Q_{fountain}$) measured weekly between 31 May 2011 and 5 October 2011.

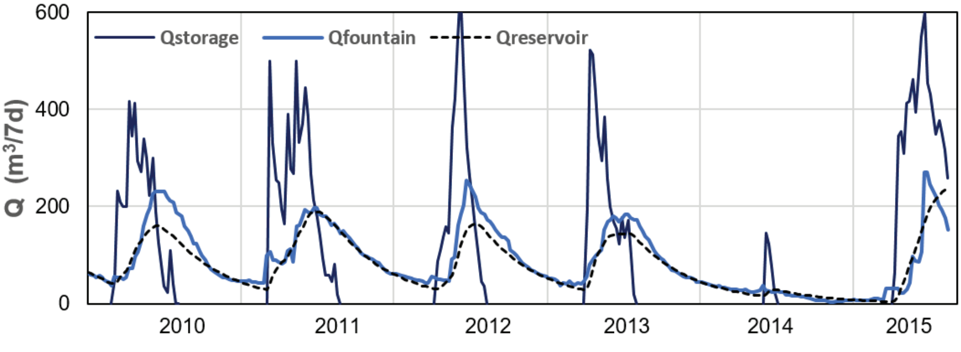


Figure 9 - Infiltration inflows to aquifer of East Pond 1 (fluctuating line with sharp peaks) based on measured groundwater storage level, fountain outflow extrapolated (round solid line), outflow into the pond computed by linear reservoir routing (round dashed line). Note the dry year 2014.

6. QANATS IN SUFI VILLAGE, NORTHWEST IRAN

A still functioning example was selected from Sufi Village located near Maku in West Azerbaijan province, Northwest Iran (Figure 10). The Sufi River crosses the center of the village and drains its area of 45 km^2. It is 14.65 km long with 5.75% slope. Mean elevation of the drainage area is 2008 m above sea level and concentration time is 2 hours. The climate of the region can be considered as semi-arid cold with mean annual temperature of 15°C and 295 mm annual precipitation. The village is home of three qanats named Amir, Dirsak and Choupan Goli. As reported [40], the qanat system has an average outflow between 4.0 l/s and 13.2 l/s.

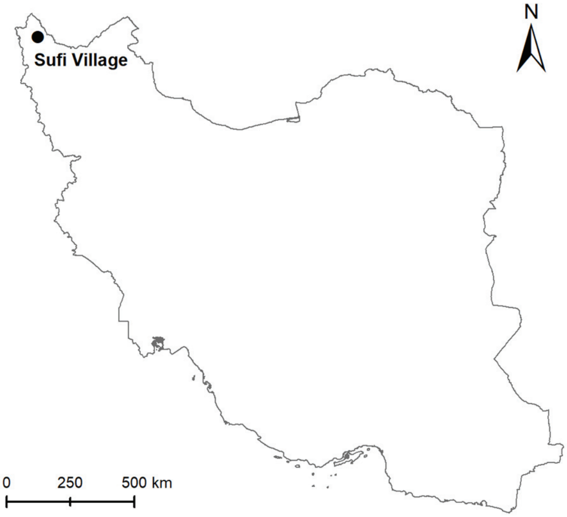


Figure 10 - Location of Sufi Village near Maku in West Azerbaijan province, Northwest Iran.

The Sufi Village qanat system was improved with the so-called underground or submerged sand dam constructed in the Sufi River. This is a technical term used for a structure to store water of an intermittent river within the sand and gravel of the riverbed. It is apt for riverbeds of bedrock or in other impervious material filled with gravel and sand. A wall of about 1-m width is built of rubble concrete or masonry in a trench across the river up to the gravel surface level (Figure 11). Stepwise the trench is refilled with gravel supporting the wall against horizontal forces. The wall is blocking the gravel zone of the river. In the rainy season, flow which would otherwise go downstream is retained filling the interstices of the gravel behind the wall. The storage volume, depending on the porosity, can make up to 50% of the gravel volume. The stored water is protected against evaporation and pollution and can be obtained by wells or conveyed to a downstream water intake system through an orifice attached to the wall as an underearth bottom outlet. The stored water is of high value in dry seasons particularly. The Sufi River case is detailed below as an example combined with the qanat system.

The underground dam in the Sufi River is used to retain and store water infiltrating during flows in the pores of the sediment upstream (Figure 12). The sediment is composed of sand or natural gravel allowing easy transmission of water. Water is discharged to the existing qanat channel (conduit) by an orifice attached to the wall as an underground bottom outlet of the submerged dam and reservoir. It is then conveyed by the qanat channel to lower areas. The qanat system reaches downstream for about 100 m to capture further smaller occasional drain water volumes.

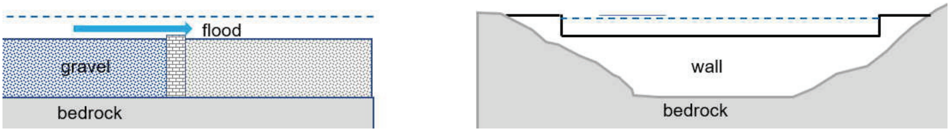


Figure 11 - Sand dam, schematic; left: longitudinal section, gravel upstream of wall storing water retained from a flood, right: cross-section, sight on the wall without gravel.

Figure 12 - View from the crest of the underground dam in Sufi River (Photo by B Vaheddoost).

For a quantitative assessment, reported discharge measurements [40] from the seventh month (Mehr) of the Jalali year 1382 (starting from 23 September of the Gregorian year 2003) to the twelfth month (Isfand) of the Jalali year 1386 (ending in 20 March of the Gregorian year 2008) were used (Figure 13). Sudden rise is visible in the first month (Ferwerdin) of the Jalali year 1386 in the Amir qanat after the upstream underground dam was completed.

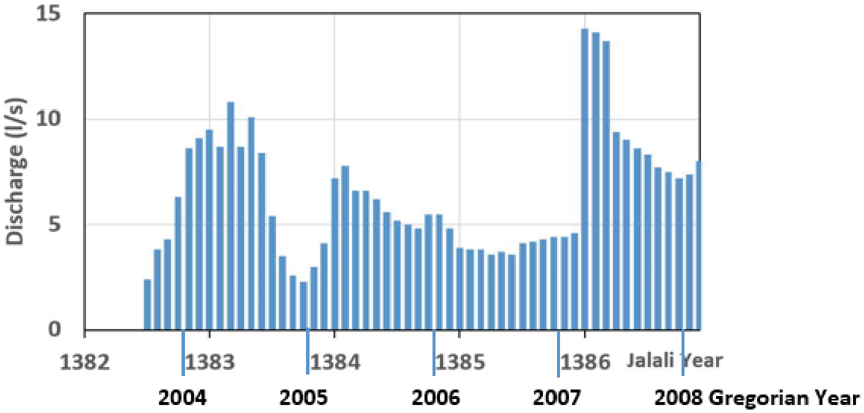


Figure 13 - Monthly mean discharge at the Amir qanat with a sudden rise in the first month of the Jalali year 1386 (March in the Gregorian year 2007) after construction of the underground dam (Data from [40])

7. AN INSIGHT FROM ENGINEERING POINTS OF VIEW

7.1. Drought and the Decline of the Hittite Empire

The decline and abandonment of Hattuşa began around 1200 BC. During this period, famines due to low rainfall in the Greater Region are historically documented. At the time of Pharaoh Merenptah (1213-1204 BC) the Egyptians delivered grain to the Hittites to cope with a famine that had occurred there [41]. A series of 'dry years' in 1198-1196 BC with little precipitation, which showed the character of prolonged droughts, not only led to the failure of the grain harvests, but also prevented the supply of water in the ponds and thus initiated the abandonment of the city [12].

The dry year 2013-2014 with its measured values gave the opportunity to understand such a situation. In 2013, the Çorum meteorological station of Turkish State Meteorological Service (Devlet Meteoroloji İşleri) recorded the lowest annual precipitation of the time series 1929-2018 with just over half of the mean annual precipitation. This is a dry year with severe drought being effective in Turkey [42-43]. The dry year has a statistical return interval of around 90 years. The correspondingly low groundwater recharge brought the water level in the east ponds only for a short period of time above the threshold level while, in the south ponds, it remained below the measurement range. The southern ponds would not have been filled, the eastern ponds only slightly. Figure 14 shows the groundwater level below the terrain level of the two measurement points and above the annual precipitation. The dry phase and the recovery in 2015 are evident. The southern ponds were taken out of service earlier, probably due to unreliable filling. A longer series of years with little precipitation will also have restricted the function of the eastern ponds and contributed to the decline of the empire.

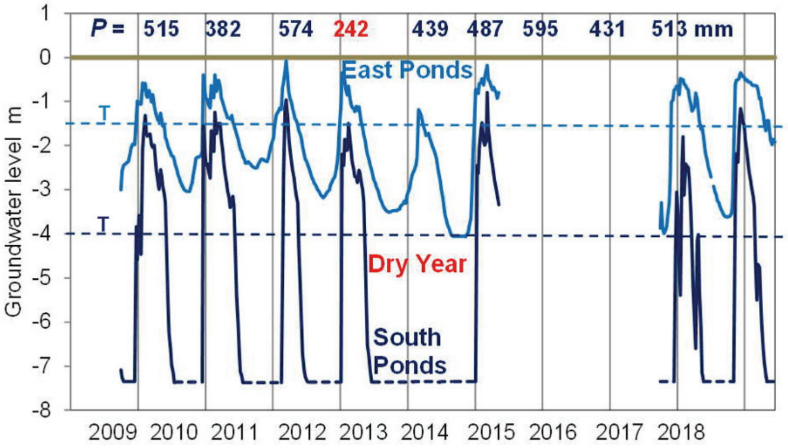


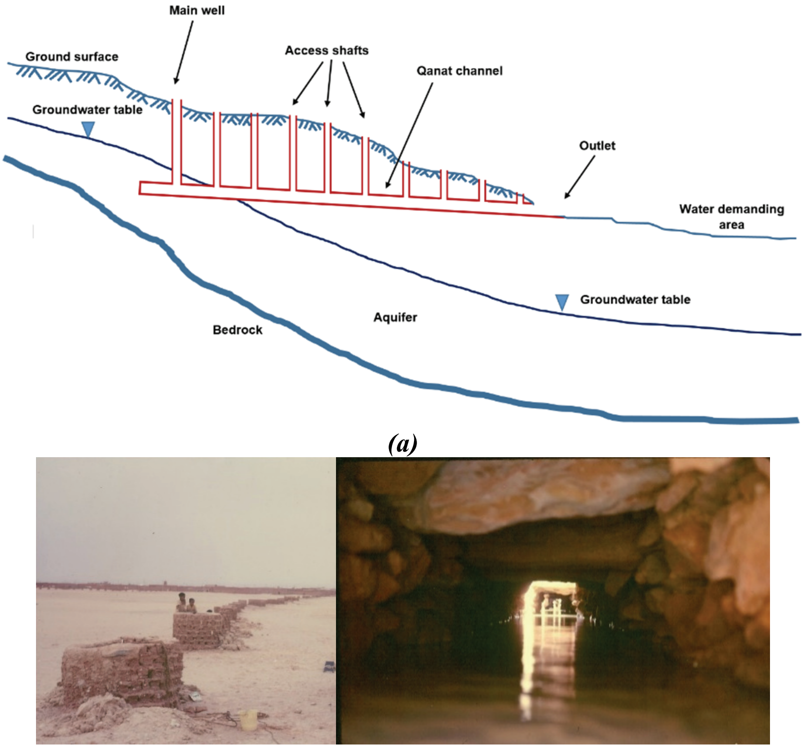
Figure 14 - Measured groundwater levels in 2009 – 2018, South and East Ponds, with annual precipitation P (Çorum) and threshold levels T, above which groundwater could discharge into the ponds. The data gap 2015-2017 was simply caused by loss of the hand-written data sheets of this period.

7.2. Hydraulic Engineering about Qanats

Qanat technology is understood as a further development of the 'cut-in' method described above for extracting ground and strata water. Instead of simply opening up the aquifer where it meets the ground surface, a 1- to 2-m diameter tunnel is driven into the aquifer. Well-like vertical shafts are dug at regular intervals, first for removing the excavated material, then for maintenance and ventilation (Figure 15a). Craftsmen who excavated the qanat were called *Muqanni* in Farsi (the qanat-diggers). Stabilized by rough rubble masonry to withstand collapse, the gallery (Figure 15b-c) receives water draining from the aquifer and transports it by gravity to the outlet. The gallery typically follows the slope of the ground surface or aquifer, but other slopes can be used where appropriate. Structurally, qanats are resistant to natural or human-made disasters; e.g. earthquakes, floods or wars. In spite of the old background, there are still qanats actively in use.

This evidences that the way of thinking and the engineering approach of the ancient water supply systems was evidently similar, if not the same, as today's engineering practice. With machinery and much better-established theories it is possible to replicate the ancient water systems in hydraulic engineering for sustainable water resources development projects, for groundwater particularly. The modern water chambers and well rooms are based on the principle of opening water-bearing layers, as used for the qanats.

The discharge rate of qanats is traditionally determined by volumetric flow measurements at the downstream outlets, while modern systems are now available. The physics behind the technology is almost the same as the classical drainage systems, that water is discharged naturally by gravity given by the hydraulic gradient and the soil conductivity of the aquifer and the cut surface area. In the qanat, it is the slope of the channel (the almost horizontal conduit) transporting the outflow.



(a)

(b) *(c)*

Figure 15 - (a) A typical longitudinal view of qanat showing main elements of the system, (b) top entrance of vertical access shafts on the ground surface, (c) qanat channel (Fogara at Adrar, Grand Western Erg, Algeria, year 1965, Photos by H Wittenberg).

8. CONCLUDING REMARKS TO THE ANCIENT TECHNOLOGICAL HERITAGE

In the case of the ponds, as well as of other Hittite reservoirs, such as that of Alacahöyük (~1250 BC), the risks of strongly fluctuating and often violent surface inflows were avoided by opening near-surface groundwater and strata aquifers. The technology improved the water supply and the prerequisites for the development of Hattuşa into the capital of a great empire. After this success by 'cutting-in' water-bearing layers on the slope, it was only logical to achieve even better results by 'penetrating'.

The 'cut-in' technology can be regarded as a preliminary stage of the qanat systems, in which tunnel-like drainage conduits allowed the extraction of larger groundwater flows throughout the year in a more sustainable way. Qanats, as an ancient invention, are appropriate for supplying water in arid and semi-arid regions as they are little affected by the fluctuation of surface waters and prevent groundwater overuse.

Spring captures and well rooms of today are also based on the principle of opening water-bearing layers. An engineering points of view insight shows the non-machinery human-powered or gravity-oriented ancient simple techniques have been fundamentals for today's machinery-powered complex technology. The way of thinking and the approach of the builders of antiquity were evidently quite the same as those of today's engineers, even without machines and theoretical foundations. Their works were fundamental for today's methods. Qanats can still be considered among appropriate water supply methods in arid and semi-arid areas despite the availability of modern equipments such as pumps allowing the withdrawal of higher discharges from deeper groundwater levels.

Perhaps it is more important to emphasize that the qanat technology has contributed to civilizations by helping the settlements; e.g., villages, to form and supported cooperation among water users by sharing the available water for their demand. The qanats might have better overcome deficit in surface water during drought, and thus might have prevented or delayed the collapse of the Empire if they would have been known by the Hittites.

Symbols

I : Slope of groundwater surface
k : Recession constant (day)
k_f : Hydraulic conductivity (m/s)
n_{eff} : Effective pore volume (%)
Qi : Inflow discharge (m^3/s)
Qo : Outflow discharge (m^3/s)
S : Groundwater storage (m^3)
t : Time (week)
v_f : Flow velocity (m/s)
Δt : Time interval (week)

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