Water resource management in ancient Iran with emphasis on technological approaches: a cultural heritage
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ABSTRACT
Water is an essential component in the history of Iran. Due to the unfavorable distribution of surface water and the fluctuation of yearly seasonal streams, to fulfill water demands, ancient Iranians have tried to provide a better condition for utilization of water. Accordingly, elegant designs like qanats became an indispensable element of hydraulic systems, while institutional frameworks were innovated to be combined with in water resource management. Evidence shows that hydraulic structures and water establishments date back thousands of years known as cultural heritage. Besides, the ancient Iranians have realized the importance of an organization to supervise irrigation and water conveyance. Thus, during the Achaemenid and Sasanian Empires, water engineering was developed significantly through the whole territory. The governmental endorsements associated with contemporary engineered structures have made extensive innovations in water systems, such as canals, watermills, water treatment, water storage, piping and construction. The infrastructure fulfilled a wide range of necessities of a civilized country and assisted in achieving its golden era. Consequently, this paper is aimed at studying ancient water resource management and technological approaches in Iran.

Key words | ancient Iran, cultural heritage, institutional framework, technological approaches, water resource management

INTRODUCTION
Iran is mostly an arid or semi-arid country, with a subtropical climate along the Caspian coast. Of the total area, 13% is covered by cold and mountainous weather, 14% is moderate and the remaining 73% has dry weather. Annual precipitation over the region is near one-third of worldwide average (271 mm), while evaporation exceeds three times that. Also, little correlation exists between rainfall and agricultural water demand intervals. Besides, upstream runoff is often torrential, especially where the catchment area is relatively small. This leads to unpredictability in the water resources availability, difficult handling and predominantly adverse sediments. All these factors lead to a reduction in the agricultural potential (Oosterbaan 2010), forcing Iranians to seek for water and invent consistent technologies (Hobbevatan 2009).

Modern civilizations emerged as irrigation systems were developed that significantly increased the total food supply. The earliest civilizations were all located on rivers and fertilized lands. Anthropological studies have revealed that the oldest irrigated agriculture in the Near East Region was practiced in Egypt around 5000 BC, and is as old as the practice of agriculture itself (Bazza 2006).

About 4500 BC, successive waves of people migrated into a land which is now called ‘Iran’. We know them as the Aryan/Sumerian, ancestors of Iranians (Ghirshman 1954). Discoveries prove that these people cultivated land and raised crops in the third and second millennium BC. The Achaemenid Empire (550–330 BC) was the first of the Iranian empires to rule in the Middle East and central Asia (Ghirshman 1954). This empire was extended from the Indus...
River to the Aegean Sea. Therefore, the socioeconomic structure of the empire was characterized by extreme diversity. The predominant form of economic activity was agriculture (Dandamaev & Lukonin 1989; Koch 1990; Dandamayev 2009). The expansion of the agrarian economy reached a summit under the Sasanians (224–651 AD) as well. The private property was not limited to land, but also included canals, qanats, and mills. The intensive agriculture practiced under the Sasanians both ensured production of agricultural surpluses and required construction of considerable infrastructure, which particularly was connected with irrigation. Only associations of individuals or institutions could make authoritative decisions and engage technically trained personnel. This hydraulic infrastructure was equally indispensable in supplying water to cities, where population growth went hand in hand with high agricultural yields and the manufacturing and commercial activities that they supported (Wenke 1975; Adams 1981; Rahimi-Laridjani 1988; Gasche 1994).

Consequently, regarding rainfall scarcity, the vital dependency of agricultural communities on water, the history of emerging civilizations and the incentives of governments in constructing infrastructures, some elegant technologies and frameworks were introduced in ancient times. Thus, in this paper, based on wide research over ancient water structures; the institutional frameworks and technological inventions related to cultural aspects are reviewed. For this purpose, water management, water transfer structures comprising qanats and pipes in association with ancient technologies in construction, water treatment and storage are mentioned as follows.

**RESULTS AND DISCUSSIONS**

**Institutional framework for water management**

The first known regulations related to water date back to the era of the Babylonian King Hammurabi (1792–1750 BC), with the elaboration of a code of law based on previous Sumerian laws. Considering the importance of farmers’ cooperation in irrigation management, to ensure a fair distribution of water and to avoid conflicts, the code introduced three main concepts related to water management: (1) proportional distribution whereby the farmer receives water in proportion to the amount of land he works; (2) definition of an individual farmer’s responsibility towards the whole community (i.e. by safeguarding the sections of public canals that lie on his property, accepting community rules such as water turns and liability for damage caused to neighbors owing to negligence or malice); and (3) water apportionment and policing of irrigation arrangements as a collective responsibility of beneficiary farmers. These concepts constituted the foundations of irrigation development in the region. As an incentive to encourage the construction of agricultural hydraulic works, during the period 550–331 BC, the Persian rulers encouraged qanat builders by legally allowing their heirs to retain profits from newly constructed units for five generations (Bazza 2006).

An important factor in water harvesting, maintaining, conveying and distributing is water resource management, which is indispensable to have an independent organization. This type of organization became sophisticated from the early times of Achaemenids, and reached its technological zenith during the Sasanian dynasty. This organization under Sasanians was called ‘Divan-i Kast’ or ‘Fozun’ and the respecting regulation was called ‘Namak’. The ownership of the numerous qanat varied from private to community ownership. In cases of having a long qanat, the land beneath may have several owners and the water was traded. Some landlords endowed the qanat routes under their lands partially or totally to the whole community they served. Accordingly, the ownership and distribution rights have developed over hundreds of years. Sometimes, the distribution rights were determined by negotiations through representatives. For example, a salaried official known as Mirab was elected by the users or appointed by the officials to determine water distribution (Eduljee 2007a). Recently, some Bactrian documents are discovered about land-sale contracts, legal judgments, sales receipts, tax-lists, and letters representing the institutional framework of Sasanians (Daryae 2008; Rezakhani 2008).

**Types of water transfer structures**

**Qanat**

To make use of the limited amounts of water in arid regions, as early as the fourth millennium BC, the Iranians developed the first man-made underground water channels called
‘qanats’ (Esfandiari 2008). Qanats apparently originated in pre-Archaemenid in Iran and spread to Egypt, the Levant and Arabia in Achaemenid times (Ward English 1968). In fact, qanats may be considered as the first long-distance water transfer system carrying water to remote dry areas and linked wells along their trail for irrigation and domestic use (Motiee et al. 2006). The water source is the tunnel which reaches down and into the water table. The other shafts provide ventilation and give access for cleaning and repairing the conduit tunnel below (Laureano 2012). This application of qanats in Iran was also reported before Persian kingdoms by Assyrians (Eduljee 2007a; Al-Taiee 2012).

Establishing the proper size and gradient of a qanat requires experience and knowledge of surveying, geology and hydrology. Qanats should not be too steep for adverse hydraulic effects while needs to be of a size large enough to accommodate repairing and maintaining the tunnel (Eduljee 2007b). The critical and primary step in qanat construction is identification of an appropriate water source. The search begins at the point where the alluvial fan meets the mountains or foothills. Because, water is more abundant in the mountains due to orographic lifting while excavation in the alluvial fan is relatively easy. The muqannats (professional qanat diggers) followed the track of the main water courses coming down from the foothills to identify evidence of subsurface water such as deep-rooted vegetation or seasonal seeps. Then, a trial well is dug to find the location of the water table and determine whether a sufficient flow is available to justify construction. If these prerequisites were met, then the route was laid out above ground (Kheirabadi 1991; Ward English 2009).

This technology was gradually applied by farmers. Extensive application of qanats not only relies on its workability but also in incentives the rulers made for qanat builders and their heirs. Hence, from this time, the system expanded through the territory (Al-Taiee 2012) and the world thereafter. Some examples of ‘qanat-aquaduct’ combination systems in Tunisia and Turkey are witnessed (Bazza 2006).

This technique is still in use in Iran for various purposes including irrigation. There are about 22,000 qanats in Iran with 274,000 km of underground conduits of which 70% operate particularly in Bam, Yazd, Kerman and Isfahan. The amount of water produced from the qanats in use is estimated at 750–1,000 m³/s in aggregate. In 1933, all of Tehran’s water supply was provided from qanats. The oldest and largest known qanat exists in the city of Gonabad (northeastern Iran, Khorasan province) which, after 2,700 years, still provides drinking and agricultural water to nearly 40,000 people. It is 70 km long with 470 shafts and maximum depth of 340 m. It has been declared a UNESCO world heritage site (Boustani 2009).

Canals

Different water transfer structures have been constructed over the last 3,000 years. One of the most popular is called ‘Jouy’ which is translated in English as ‘Canal’. The word canal is deprived from Arian language. There, the word ‘cal’ was used in names of many streams and rivers. Some of these canals are shown in Figure 1 (Javaheri & Javaheri 2009; Sadrzadeh & Badalians Gholikandi 2010). Communities that constructed and applied qanats, used a jube, an above ground gutter, as part of an urban water and runoff collection system. There, the water which was not suitable probably for drinking was used for irrigation (Eduljee 2007a).

Pipes

Ancient Iranians used pipes made of clay to conduct water. These pipes were manufactured similarly to bricks and containers. To avoid being cracked or broken during Figure 1 | Four different canals: (a) quadrilateral shape (Dehrood River), (b) Bilabial (Nagh Dokhtar river), (c) G shape (Daralaman Ij castle), (d) C shape.
construction or transportation, theoretically they could be produced in 30–60 cm lengths. Practically, however, due to special method of waterproofing, the total length was limited to 45 cm. The pipes were assembled as shown in Figure 2(a), where inflow was from the larger side (diameter of 15–17 cm) to narrower space (diameter of 12 cm). To make the joints impermeable, usually a young worker with smooth arm filled the voids with Sarooj, a mortar, and polished them. Therefore, the pipe length did not exceed 45 cm, to make work possible. This method is observed in remnants of Persepolis and its application continued until 100 years ago. Moreover, to keep pipes stable, the foundation was made of bricks and filled with Sarooj mortar (Figure 2(b)).

On a larger scale, such as for chutes in dams or tunnels, these pipes could be used with the diameter of 80 cm at most. Hence, a more condensed foundation is required for water conveyance systems in high pressure. In Figure 2(c), the components of a chute foundation in ‘Daralmizan’ dam is illustrated (Javaheri & Javaheri 2006). Using mortar with crushed stones in two different layouts (laminated and mixed), tolerates internal and external loads remarkably well.

Types of technological invention

Considering that a qanat is not only a prevalent and efficient structure for water transfer but also a water resource itself, different water structures can be combined with it. For instance, water mills can be charged through its energy; ventilation and cooling system can be implemented and by soil specifications, water treatment advances. Some of these inventions are described.

Watermills

One of the skills possessed by ancient Iranians was to make use of the water’s hidden power to rotate the stones of the watermills (Figures 3(a), 3(b)). The roof of this building was usually a dome while light and air were supplied through a door. Qanats made it possible to build many watermills rotating with the force of groundwater. According to the way in which the watermill drew on the energy, it could be classified in two groups either as a potential watermill (chute watermill) or as a kinetic watermill (wheel watermill). These two types are based on the difference between the water head of input and output. In kinetic watermills, the axis is horizontal, drawing on the water flow directly; whereas in potential watermills, the head difference of inflow and outflow should be built artificially, so that the required energy would be generated (Khaneiki & Semsar Yazdi 2008). The mill shaft was semi-conical in shape and its diameter reduced gradually from top to the bottom. This shaft could be plugged by a wooden device which was accessible through a narrow gallery from inside the mill. The wooden turbine consisted of a wooden axle with a diameter, which gradually increased as it went down. Both ends of this axle were generally made of iron. The upper iron tip of the axle was fixed in the upper millstone. This axle was surrounded by paddles and the whole system was known as the turbine wheel. When a water jet impinged forcefully on the turbine wheel, it rotated, and this in turn caused the upper millstone to be turned while the lower millstone was stationary. Thus, the grain could be ground by the rotation of the upper stone on the lower. There was a hole in the middle of the upper stone used for the grain to be discharged into the space between the two stones. The two millstones were not truly horizontal, but slightly inclined which helped the flour to be discharged into the flour bags (Sanizadeh 2008; Pourjafari et al. 2010). The fate of these watermills was like others throughout the world as the industrial revolution evolved.

Ice and water storage

In 400 BC, Iranians had mastered the technique of storing ice in the middle of summer in the desert. The ice-house, called a ‘yakh-chawl’, was a large underground space (up
to 5,000 m³) that had thick walls (at least 2 m at the base) made out of a special mortar called ‘Sarooj’. The space often had access to a qanat, and contained a system of wind traps (Simmers 2010). Ice houses consisted of five components: pool, shade wall, ice storage pit, dome, and a wind tower. During winter, a measured amount of water was channeled into the pools where it was frozen at night. The shade wall surrounding the pool protected the ice from being melted by sunlight. In the morning, more water was added to the pits. In this state, a block layer of ice was built up. As the ice in the pit reached a particular thickness, it was broken into blocks and transferred to the ice storage pit. Typically, this chamber was covered by a conical dome. The temperature in the ice storage remained low enough to preserve a fair quantity of ice for a year. Wind towers and qanats formed a system to cool the interior down and thereby keep the melting of stored ice at a minimum. An ‘Ab-Anbar’, a water storage tank, was kept cool by this method as well (Figure 4). A wind tower is a chimney-like structure positioned above the building; of its four openings, the one opposite the wind direction was opened to move the air out while the incoming air was sucked in from a qanat below. The air flow across the vertical shaft opening created a lower pressure and drew cool air up from the qanat tunnel, mixing with it. This air was drawn into the tunnel at some distance away and was cooled by contact with both the cool tunnel walls and water. In dry desert climates, reduction in the air temperature exceeded 15 °C. Hence, the basement was kept cool and only comfortably moist (Bahadori 1978). These days, the principles of the cooling system can be tracked like industrial structures but ice storage buildings, by emergence of electricity and refrigerators, are completely ignored as part of cultural heritage.

Sarooj

Long before Portland cement was invented, Romans used pozzolans as an additive in mortar making it stronger. Volcanic ash provides the required flexibility of silica while many centuries ago, in the Middle East, pastoral societies used the ashes of burnt animal husbandry waste or ‘Shaltook’ (rough rice) instead. Mixing this ash with lime and
clay constitutes a widely used mortar in ancient times called ‘Sarooj’. The capability of polishing in association with its impermeability is the main specifications of Sarooj but the disadvantage is its slump and shrinkage after water loss. As a result, cracks appear and expand leading to adverse effects on impermeability. Removing these cracks, similar to steel bars on modern concrete structures, some reinforcements comprising special plant stem called ‘Loui’ (Typhaceae), goats’ or camels’ wool, young men’s hair or ‘Kah’ (straw) were used for different applications. For example, hair as a reinforcement is mostly used in furnaces or places with the probability of concentrated stress while plants are applied in flat and thick surfaces. Due to the specification of reinforcement, they could well be mixed with other components and do not cause any roughness especially in hydraulic structures. When the constituents of Sarooj were not available, fine sand was an alternative but could not be replaced perfectly and still required clay or white egg in some cases. In order to form Sarooj, clay and lime are mixed together at a 6–4 ratio and are worked for 2 days. By this time, reinforcement (Loui) and ash are added and worked with 10 cm diameter wooden bars, by humans or goats. In the final step, to reduce porosity and increase workability, castor oil or white egg is added. Then, this mortar is ready to be used with some caution. For instance, surfaces like roof tops in arid regions which are in direct contact with temperature fluctuations should be constructed instantaneously. Otherwise, structural cracks would lie within (Javaheri & Javaheri 2006). Sarooj has proper strength with more impermeability rather than cement for water system construction such as channels and bridges foundations (Al-Rawas et al. 2005). The roughness coefficient in Manning equation of Sarooj used in channels is about 0.012, while can be reduced using castor oil as a polisher. These can result in head loss reduction and cost-effective projects especially for long distances as found for qanats. Yet, due to its lower competence in workability against modern cements, it has been replaced mostly in cities rather than rural areas.

**Water treatment**

The oldest natural water treatment system was built approximately 3,000 years ago located next to the Ziggurat of Chogha Zanbil in the city of Susa (Yazdi 2012). After a primary sedimentation basin, there was a reservoir for treatment with 350 m$^3$ volume and insulated with a layer of natural bitumen (Sanizadeh 2008). The water was treated by passing through various layers of sand, gravel and coal. Also, a quantity of salt and lime was added for disinfection. Then, the treated water was transmitted to smaller basins through nine narrower canals beneath the main reservoir.

The qanat of Kish Island is more than 2,500 years old, and currently it has been converted into an underground town at a depth of 16 m below the surface, with an area of more than 10,000 m$^2$. The ancient water management system collected water from 274 wells and sent it to a central filter shaft. It was filled with three layers of filtering material. The top layer was coral gravel which was used to neutralize the acids and remove coarse solids in the water. Then a layer of coral grit with clay was filtering fine solids, and the lowest level was made of marlstone, a special lime rich mud. By passing water through the layers, the quality differed in depths and used for various purposes. After the first level of filtration, it was used for field irrigation, and the best quality treated water at the bottom was for drinking. Also, there were even underground tunnels which allowed sailing boats to enter the lowest level and collect drinking water from the deepest well (KTA 2010). The method of water allocation relating to its quality is known as part of water resource management in modern life. Besides, the principles of filtering water have remained for centuries. Yet, because of the loss of qanats for water transfer, this combination for water treatment has become cultural heritage.

**CONCLUSIONS**

This research is aimed at studying water resource management in ancient Iran with a focus on technological approaches. It has been shown that an elegant contemporary expertise as found in the construction of qanats could well be applied in combination with other systems to make technical innovations. As discussed, this became practical when governmental endorsements provided incentives to hydraulic structure builders.
Accordingly, during the Achaemenid and Sasanian era, the expansion of the agrarian economy reached a peak driven by these infrastructures. Water mills, ice and water storage pits, water treatment systems and application of an efficient mortar called Sarooj have fulfilled a wide range of the necessities for a civilized country and assisted in the achievement of its golden era. All these ancient technologies have been founded on the application of scientific principles. These standards have been similarly used for modern techniques which emerged about 100 years ago. Up to then, this integral water management has been founded within Iranian cultures and was barely replaced with modern technologies.

As the materials and methods discussed were locally available, green and energy saving, these constructions could be categorized as environmentally and economically sound options. Besides, the principles, expansion and durability of these systems prove their efficiency. Yet, their sustainability alone could not be compensation for their low competence in workability compared with more modern systems. Therefore, at the present time, their application is confined to particular regions.

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