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A REVIEW ON THE QANATS IN IRAN AND THE TANK CASCADE SYSTEM (TCS) IN SRI LANKA – PARALLEL EVOLUTION BASED ON TOTAL ENVIRONMENT

H.A.H. JAYASENA[1,*] AND K.R. GANGADHARA[2]

[1]*Department of Geology, University of Peradeniya, Peradeniya, 20400, Sri Lanka*
[2]*General Treasury, Ministry of Finance and Planning, Colombo, Sri Lanka*

[*]*Corresponding Author: e-mail-cjayasena@pdn.ac.lk*

ABSTRACT

Water supply to arid areas by many ancient communities around the tropical and subtropical regions was unique, where the conveyance mechanism had been developed based on morphological, geological and meteorological factors. However, to maintain the longevity and sustainability of these water supply systems, effective environmental management is imperative. Many medieval communities throughout these regions have practiced runoff harvesting to groundwater conservation in order to lead a sustainable life with the available rainfall. We postulated that integrated environmental criteria based on sound technical principles were fundamental for the establishment of the Tank Cascade (TC) and the Qanats irrigation systems. To carry out a comparative study and to investigate such mechanisms, we selected a dry zone catchment in the northwestern province of Sri Lanka and a Qanats based irrigation system in Iran. The TCS has evolved as a network of hydraulic structures, which have harnessed the surface runoff. The small tanks within the TCS were organized into cascading systems in order to recycle and reuse water in micro-catchments. On the other hand, the qanat system is operated with successive wells joined by a horizontal conveyance canal and fed by the groundwater in the foothills. The evolution and existence of both these systems as they operated within the total environment seems significantly similar except the fact that rainwater harvesting for the Qanats is with groundwater while for the TCS it is surface runoff. Similar to Qanats, the TCS is also invented on the simple technology of utilizing gravity to channel water from foothill areas to agricultural lands and settlements in lowland areas. As the Qanats depend on the groundwater in regions with very low annual rainfall of 100–500 mm, the TCS in semi-arid regions depend on surface runoff received through annual rainfall less than 1250 mm. The longevity and effectiveness of those systems depended on appropriate management. Though the Qanats system seems to have problems at present, it could be revamped by implementing necessary policy decisions while making due changes according to a systematic and an integrated plan. On the other hand, the TCS is operated under a better mechanism where irrigation department and local authorities are geared enough for a water management through systematic planning and effective operation. Both the Qanats and the TC irrigation systems have evolved in parallel paths with strong similarities with their hydraulic behaviors, aerial distribution, morphological framework and social cohesion.

***Keywords:** Sri Lanka, Iran, Tank cascade system, Qanats, Total environment, Hydraulic civilization*

INTRODUCTION

Irrigation practiced by many ancient communities in the world produced unique systems, which depended on morphological, geological and meteorological factors. It is still difficult to postulate how the ancients have developed water transmission methodologies since such mechanisms were endowed with aura of myths as one can observe within the cultures associated with the TCS or the Qanats irrigation systems. However, the social organizations have played a key role for the longevity and efficient management of these systems. In the historical periods, very tight socially motivated and strictly guided moralities had been adhered by the village leaders in order to maintain an effective water management system (Geiger, 1958; Nicholas, 1964; Weeraseikara, 1955).

Medieval communities in many parts of the world have practiced different rainfall harvesting methods and adapted groundwater conservation techniques in order to lead a sustainable life (Hassan, 2004; Barker and Molle, 2004; www.wrm.or.ir, 2004). Irrigation in those regions had been a powerful tool for human advancement as evidenced by archeological findings even 6000 years before present (Jacobsen and Adams, 1958; Postel, 1999). As farmers strive to meet the food demands of ever-increasing population, the irrigation remains a cornerstone of agriculture today.

The populated townships connected with trade as early as 5000 BC and along with the silk routes and subsequent trade routes seem to be a specific reason for widespread distribution of ancient irrigation systems (Mendis, 1999; Possehl, 2002). The demand for water is very high and harnessing available water for agricultural activities needs technology and human intervention. A number of irrigation systems are operating in the tropical and subtropical countries. Among them Qanats in Iran and surrounding countries (English, 1968; Bonine, 1989; Lightfoot, 1996; Malakani, 2000), oasis in central Asia, irrigation connected with Amu Darya (Fuchinoue et al., 2002), groundwater usage in Turkey (Tolstov, 1969) and the Tank Cascade System (TCS) in Sri Lanka (Madduma Bandara, 1985), can be highlighted (Figure 1).

The longevity and sustainability of such irrigation systems as operated within the total environment implied sound technology and widespread advancements. In parallel to the above, a number of other irrigation practices by communities such as Hohokam along the middle Gila River (Huckleberry, 1995), Mohendojaro Harappa in Indus valley and Maya and Inca in the central America are also provided insights into the efficient use of available water towards their development process (Netherly, 1984). However, these irrigation systems have been challenged by newer hydraulic and agricultural technologies in each of these areas as evidenced by recent years. For instance, one can highlight water siphoning, pumping and drilling for groundwater or water supply to large-scale cash crop farms. Nevertheless, water deficiency is still a major constraint for the well-being of the people in the dry regions of the world, which provides alarming statistics (Table 1) (Postel, 1999). The irrigation systems as described above have been successfully operated conjoined with integrated total environment, which encompass the needs of the society without significantly altering and sacrificing the physical and the biological environments. This paper emphasized practice of different irrigation systems especially in the tropical and subtropical regions while attempting to identify roots and parallelism among irrigation techniques, water conservation and management methods, maintenance of conveyance structures and interdependency for available water through social integration.

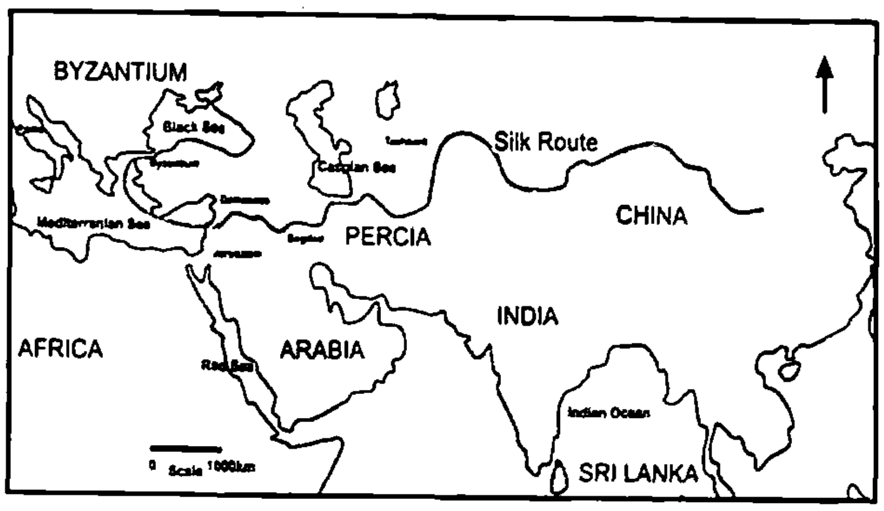

Fig. 1 Ancient hydraulic civilizations centered in tropical and subtropical regions around maritime and silk routes.

METHODOLOGY AND THE POSTULATION

For the present study, we postulated that integrated environmental criteria based on sound technical principles were fundamental for the establishment of the TC and the Qanats irrigation systems. These systems may have been originated as isolated fundamental water supply methods, however some evidence indicate that they were not simply evolved in a haphazard manner. In this respect, we approach to study and compare the TC and the Qanats irrigation systems with respect to their physical framework, covering rainfall, morphological and geological components, biological framework covering wetlands and agriculture and social framework covering sociotechnical influences as they operate in the tropical and subtropical regions.

To review and compare such irrigation practices, we selected a dry zone TCS in the Kurunegala District of Sri Lanka (Figure 2) and the Qanats irrigation system in Iran.

Table 1 Water deficit in key countries and regions - Mid 1990 (After Postel, 1999)

Country/region	Estimated annual water deficit
	Billion m^3per year
India	104.0
China	30.0
United States	13.6
North Africa	10.0
Saudi Arabia	6.0
Other	Unknown
Minimum Global Total	163.6

TANK CASCADE SYSTEM (TCS) AND QANATS SYSTEM

BRIEF REVIEW ON TANK CASCADE SYSTEM (TCS)

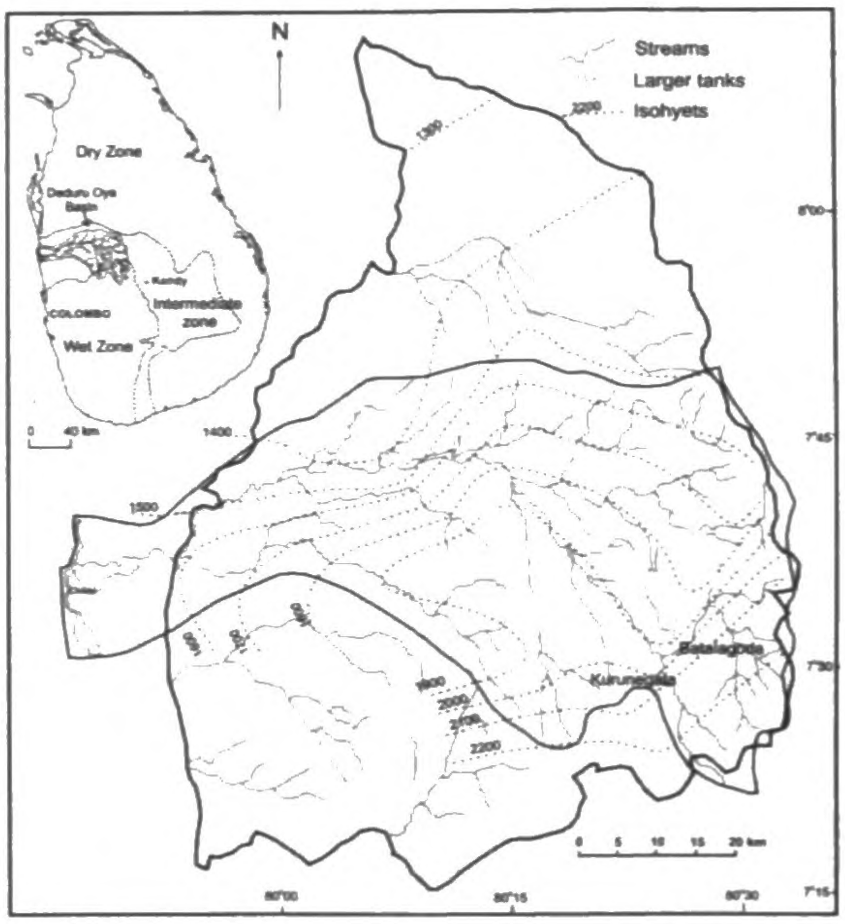

Fig. 2 Deduru Oya river basin in Sri Lanka with the climatic boundaries and rainfall variation across the Kurunegala District and beyond (Modified after Jayasena et al., 2011).

The Tank Cascade System (TCS) has evolved as a network of hydraulic structures for conservation and recycling of water, whereas the hydraulic civilization has harnessed the availability of surface and groundwater for their consumption. The TCS is defined as a connected series of tanks organized within micro-catchments of the dry zone landscape (Figure 3); storing, conveying and utilizing water from an ephemeral rivulet (Madduma Bandara, 1985).

Based on the average annual rainfall, the island is divided into three main zones (Cook, 1932; de Silva, 1952).

1) The Arid Zone, where the average annual rainfall is between 635 and 1,250 mm, is physically divided into two parts viz: the northwestern and southeastern littoral belts.

2) The Dry Zone proper, where the average annual rainfall varies between 1,250 mm and 1,900 mm.

3) The Wet Zone, which receives more than 1,900 mm of rain per year (Figure 2). The greater part of Sri Lanka receives a mean annual rainfall below 1250 mm, which, though not meager in a comparative sense, tends to be concentrated within a few months of the year (Gunewardhena, 1971).

Examination of topographic sheets in Sri Lanka shows over 18,000 tanks ("wew") apparently scattered and randomly distributed within the dry and the intermediate zones (Figure 3). Brohier (1935) pointed out that, majority of these small tanks with a capacity of less than 80 ha, were in some state of existence and either fully or partially operational with a varying degree of utilization by the society. Though many abandoned tanks are not shown in the topographic maps, field evidence indicate that the real number may exceed 30,000 (Dharmasena, 1991). However, as quoted by Panabokke (2000), a closer examination of the natural drainage patterns in relation to the location of the individual tanks reveals a distinct cascade pattern.

HISTORICAL EVIDENCE FOR PLANNING AND EVOLUTION OF TCS

PRE ARYAN TECHNOLOGY

Utilization of water ponds or even primitive tanks had been dated back to before the time of the migrant Indo Aryans (Brohier, 1956, Geiger, 1958, de Silva, 1987, Gunawardhena, 1971, Deraniayagala, 1992). According to *Mahavamsa*, an Aryan prince Vijaya successfully migrated to Sri Lanka in 543 BC. Legend states that the initial encounter took place at a water pond (Geiger 1958). This legend provides early evidence for the existence of either a detention-storage pond or a villu developed due to collapsing Miocene limestone in the Northwestern lowlands of Sri Lanka. Several historical records state that the Sorabora wewa (tank) in Mahiyangane was constructed by the Yaksa; pre Aryans (De Soysa, 1881).

Similarly, evidence for tank construction by the Naga; pre Aryans, is shown by the prevalence of snake (Naga) symbols with five or seven heads engraved in granite near ancient irrigation sites. Moreover, the depression storage ponds provided starting point for water supply in the newly civilized agriculture-dependent society of ancient Sri Lanka. The original structures constructed before the 3rd century BC were small and vulnerable.

As field evidence revealed, the ancients had tried to divert water through natural passages as developed within the jointed rocks encountered along with the tank bunds. Rock layers parallel to the strike of the foliation planes underlie most of these tank bunds (Cooray, 1984). The figure 4 shows such a structure associated with the Pinwewa tank as observed at Yapahuwa at the Kondadeniya temple. The rocks in the Kondadeniya temple with a nearby cluster of similar boulders formed from the migmatitic gneiss yielded a foliation of N 4-20° E. Pinwewa representing a small surface water body provide additional field evidence to unravel the early technological improvements in the reservoir building. A sluice carved through-rock joints was located on the northeast side. Two parallel master joints in the N 86° E direction formed the sides of this sluice. Considering the Megalithic site with archaeological remnants dating pre Aryan, one could argue that harnessing rainwater through tank (pond) system was effective even in the pre Aryan period.

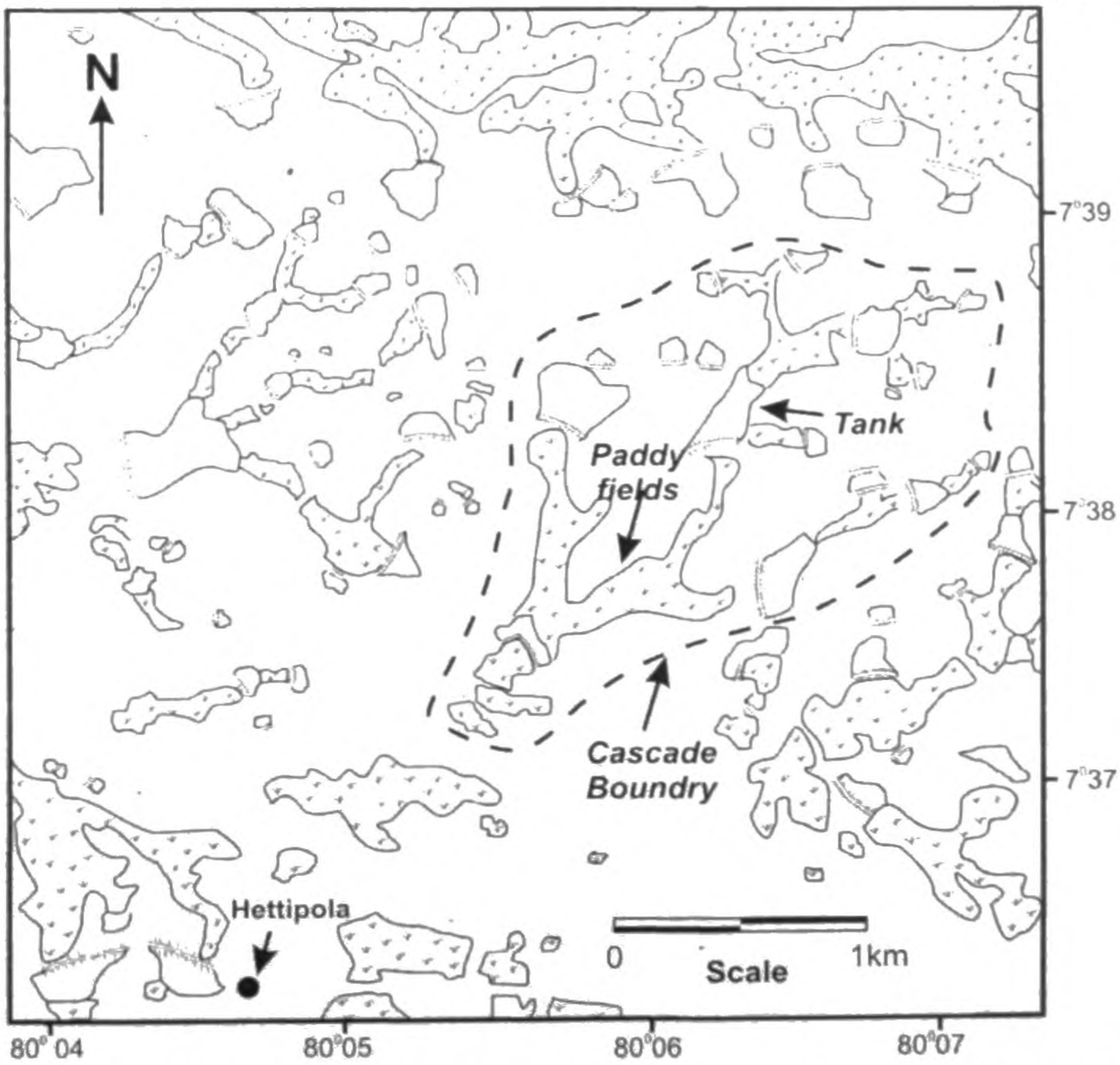

Fig. 3 Scattered and randomly distributed Tanks and paddy fields in a Dry Zone catchment (Based on topographic sheets in Sri Lanka).

POST ARYAN TECHNOLOGICAL ADVANCEMENT

Fig. 4 Water diversion through the jointed rock mass at the abutment of the tank bund.

The first written records indicate that King Pandukabhaya built a reservoir in 300 BC (Geiger, 1958). By this time engineers had invented the bisokotuwa (valve pit), the prototype of sluice regulating the flow of water from contemporary reservoirs. Therefore, credit for developing the TCS goes to the Indo Aryans (Paranavitana, 1959). However, as the technology evolved, mechanisms that are more sophisticated were introduced and subsequently bigger structures were constructed. The successful innovation of the valve pit was a critical technology. The application of technical elements such as valve pit, spillways and wetlands to the operation of TCS is still largely a mystery since no written or verbal records related to the development of such structures are available. However, one can see that runoff control and flow regulation are the main hydrologic attributes of the TCS. The runoff is easily passed through the parched land unless flows are regulated by embankments. These regulating structures are considered engineering marvels as they are able to harness large volumes of water yet are constructed only of soil and rubble. Even canals (Yoda ela 86 km by 12 m wide) and diversion channels (Elehera and Ridi bendi ela) were built in such a fashion that the sustainability of these systems could be maintained. For instance, the gentle slope and the meandering nature of these canals hinder excessive deposition and erosion along and across the channel. The planning associated with long-term management of the systems was key to this success as the engineers concentrated not only on the material that they used but also on the local physico-chemical environment. It has been reported that at the zenith of its development the ancient hydraulic engineers were even called upon to serve in other countries (Geiger, 1958).

The TCS has been a backbone for efficient irrigation in the dry zone of Sri Lanka since 1st century AD; however, additions of major structures mainly centered on Anuradhapura and Polonnaruwa during the 4th century AD and the 11th century AD respectively seem more affiliated with supplying water to the trade and city dwellers. The subsequent development and evolution of the TCS seems unique to Sri Lanka since no such advancement was achieved in the surrounding countries at this time, with the exception of South Indians, who later made use of such man-made structures (Gunawardhena, 1984). The peak of the system can be seen around 6th Century AD, however, after the 12th century AD the TCS slowly receded in use until it was revamped during British colonization of the country in the 19th century (Indrapala, 1971).

Building a tank and specially operating its functions may not be completely physical, instead, significant inputs from controlling factors through biological and social regime have been observed. These controlling factors influenced the longevity of smooth operations. For instance, recent data support that the thawulla could act as a constructed wetland (Mahatantila et al., 2005, 2008), where its functions could purify water to the acceptable environmental quality. The Kattakaduwa adjacent to the tank bund acts as a filter (Figure 5). On the other hand, maintenance of tanks was a voluntary responsibility of the users/villagers. Without the maintenance, the cycle of rejuvenation could not be achieved. As such the TCS system needs social integration in the village level to avoid its abandonment in future.

EVOLUTIONARY MODELS FOR TCS

Fig. 5 The major elements associated with village tank system (Modified after Jayasena et al., 2012).

Different models for TCS and large reservoir systems as postulated by many researchers are summarized below. It is clear that a majority of the small tanks in the TCS were hydrologically well-endowed and less susceptible to breaching during major rainfall events. Construction and associated human settlements along with more than 18000 small tanks had been identified today; without doubt, almost all these tanks were in some state of existence and were either fully or partly operational (Manchanayake and Madduma Bandara, 1999).

A number of technical factors associated with tank building are discussed in the literature, including several views on the mode of evolution of tank building in Sri Lanka. Brohier (1956) has presented a 4-stage model which Needham (1971) later supports. This model identifies: 1.) Small tanks in which water was collected and bailed out at leisure by farmers; 2.) Small tanks built in series in the upper reaches of tributaries to great rivers where water was issued by cutting the embankment at the end; 3.) Large storage reservoirs built later by "submerging or rendering unnecessary smaller ones" built earlier; and 4.) River diversion channels that convey water to augment large reservoirs and at times goes beyond the rest of the tanks to feed a number of large reservoirs further away in the tail end of the basin. Perera (1984) identified a chronological sequence of tank building from a simple structure in the ancient period to a system of major tanks and diversion scheme. However, Mendis (1985) identified a seven-stage model based on: 1.) Rain-fed agriculture; 2.) Rivulet diversion; 3.) Permanent river diversion; 4.) Construction and operation of spillways and weirs; 5.) Invention of the sluice (valve pit); 6.) Construction of small to large storage reservoirs; and 7.) Damming perennial rivers.

In recent studies based on data collected in the north central province (NCP), Tennekoon (2000) explained that construction of a tank depends on several factors such as 1.) morphology of the land, 2.) soil characteristics, 3.) the volume of rainwater received in the Maha season, 4.) the nature of hydrology, 5.) the volume of the water discharge by the upstream, 6.) size of the catchment area and 7.) the extent of land available downstream of the tanks. Moreover, most of these models summarizes that trial and error periods based on success or failure of simple check dam structures were mainly responsible for the initial stage of the TCS before subsequent establishment of sequentially larger embankments within the full-fledged TCS (Jayasena et al., 2011). Especially after the 3rd Century BC, the valve pit as it was improved and developed with solid rocks and brick structures had played a major role in building large and steady reservoirs and diversion schemes. Discussion of these models in detail is beyond the scope of this paper.

Gangadhara and Jayasena (2006) and Jayasena et al. (2011) had investigated Daduru oya basin and provided a new mechanism for the evolution of tank cascade systems based on Mahasammatha with smaller tanks to Chulasammatha with "sequence" based major tanks (Figure 6). The orderly manner of such

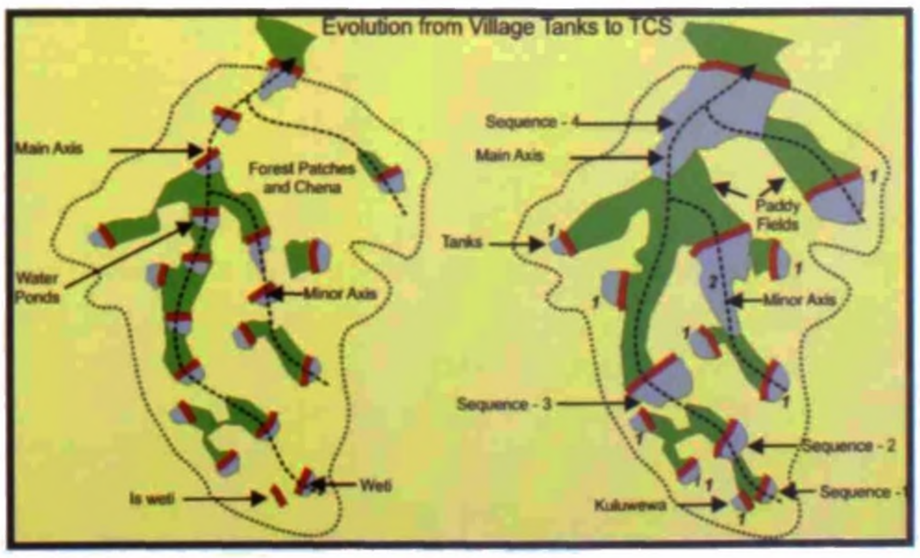

Fig. 6 (a) Schematic diagram showing progression of check dam based water ponds to the TCS and associated man-made features; (b) The nomenclature of tanks used for the analysis (After Jayasena et al., 2011).

sequencing and the resultant relationship was given by the gradient (slope) with its relevance to the geometry of the tank network (Figure 7).

The relationship was described using the term "Degree of Cascading" (DOC) as given below.

$$DOC = 10^{-[Slope]} \text{ ------------------- } (1)$$

The DOC was defined as branching of sequential tank distribution in a drainage network, which is theoretically equal to 1, if tanks were built only along a single linear basin, or approaches to infinity, if the basin has infinite branches with only headwater first sequence tanks.

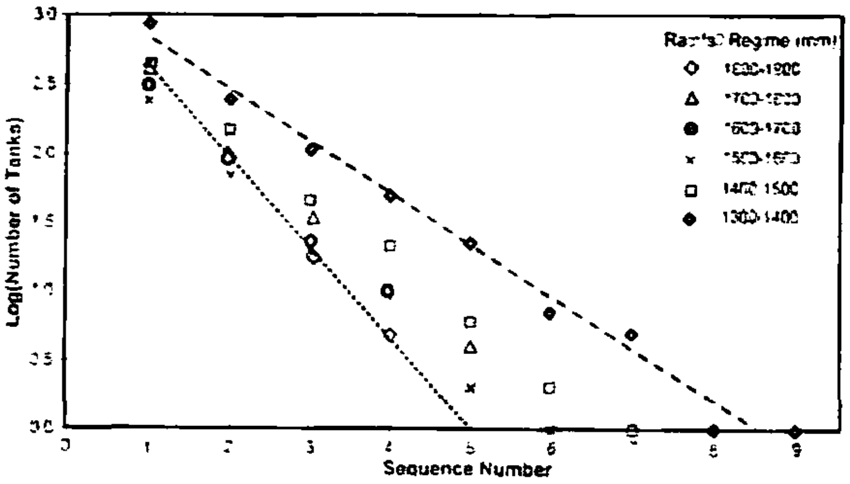

Fig. 7 A plot of tank sequence number versus number of tanks based on rainfall regime (After Jayasena et al., 2011).

The DOC represents both the geomorphologic slope and the rainfall regime; because high rainfalls with higher slope regimes represent a large number of first sequences number tanks while low rainfall with lower slope regimes represents few sequentially arranged large tanks with a higher sequence number along the basin. As observed in a case based on the Deduru Oya basin, the tank density within the TCS increases with increasing DOC (Ganagadhara and Jayasena, 2005; Jayasena and Ganagadhara 2006; Jayasena et al., 2011).

It is significant that in spite of vast changes that have been taken place in the natural, economical and socio-cultural environments associated with the TCS; most of these systems still support the civilization to its survival. However, these tanks not only supply irrigation water, but also contribute to one of the richest sources of wetland biodiversity in the country (Jayasena and Selker, 2004), and provide domestic water supplies and natural resources to millions of people. They provide direct sustenance through the biodiversity they hold, and play an important social role as the meeting place for the village (www.waterandnature.org/value.html, 2004).

Moreover, current short-term political and economic plans as well as technical inputs were not strong enough for a stable and efficient water management (Jayasena and Selkar, 2004). Therefore, it is useful to understand the nature and management of earlier cascade systems, which would provide clear insights into micro basin water management and related water-land interactions for future benefits.

BRIEF REVIEW ON QANATS SYSTEM

Qanat is rooted in the ancient hydraulic civilization where early historical records indicate its presence as far as 3000 years before present. However, farming has been a practice by irrigation water even before and evidence indicates diversion by Neolithic age; ca. 5700-2800 BC (May, 2010; Issar, 2002). Over the past 3000 years, the system of qanat has undergone many technological, social, moral, economical and legal changes that have formed an important part of Iranian culture (Yazdi and Khaneiki, 2010). The city Zarch in central Iran has the oldest and the longest qanat (over 3000 years and 71 km long) and other 3000 years old Qanats have been found in northern Iran. One of the largest known Qanats is in the Gonabad and even after 2,700 years it still provide water to the community (May, 2010; Issar, 2002).

Lightfoot (1996) defines Qanats as *"a form of subterranean aqueduct- or subsurface canal-engineered to collect groundwater and direct it through a gently sloping underground conduit to surface canals which provide water to agricultural fields"* (Figure 8). The subterranean canal is constructed by approaching through a series of wells or shafts dug through alluvial fans, bahadas and soft limestone. The well at the extreme end along the series is known as the mother well. Water seeps through the walls of the mother well which is sunk into an aquifer upslope from the fields being irrigated and then is carried by gravity flow through the qanat tunnel to a point several km away (Lightfoot, 1997). The slope of the tunnel vary from 1:1,000 or 1:1,500 for a short qanat, however, is roughly horizontal for a long qanat (English, 1998). The word "qanat" originated from the word "Kane" means digging in Persian.

The system of qanat spreads out between the latitudes 45°N and 45°S and the technology exists in more than 34 countries in the world (Abdin, 2006). A significant number of countries around the silk route adapted this technology (Figure 1).

They have continued to provide irrigation and drinking water to farms and cities well into this century, and Qanats still function in parts of China, Afghanistan, Pakistan, Iran, Iraq, Oman, Saudi Arabia, Syria, Egypt, Algeria, and Morocco. Following terms were simultaneously used to identify Qanat system in different countries. For instance, "Qanat" and "Kariz" in Iran, "Falaj" (plural "Aflaj") in Oman, "Kariz" or "Karez" in Afghanistan, Pakistan, Azerbaijan and Turkmenistan, "Ain" in Saudi Arabia, "Kahriz" in Iraq, "Kanerjing" in China, "Foggara" in Algeria, "Khattara" or "Khettara" and "Rhettaras" in Morocco, "Galleria" in the Spain, "Qanat Romani" in Syria and Jordan, "Foggara", "Khettara" and "Iffeli" in North Africa, "Galerias" in the Canary Islands, "Mombo" in Japan and "Inguttati" in Sicily. Some other terms used for Qanats are as follows: Ghundat, Kona, Kunut, Kanat, Khad, Konait, Khriga, Fokkara, etc. (Beaumont, 1971; Asghari, 2005; Yazdi and Khaneiki, 2010). Even in India Qanats are found randomly in some places. They have been identified by the name surangam (Bazzi,,2012).

A similar system is also seen associated with Mexico, Nazca Peru and Chile (Cosgrove, 2003, Abdin, 2006). The observations from America itself is evidenced for the wider spectrum of qanat distribution within the subtropical and tropical regions.

HISTORICAL EVIDENCE FOR INVENTION AND SUBSEQUENT PLANNING AND EVOLUTION OF QANATS

There are several theories put forward by investigators on the invention and evolution of Qanats. It is widely believed that copper miners in Urartu introduced the qanat technology and then introduced it to the Iranian plateau to be used by the farmers. The procedure initiated by Acadian miners who noticed some permanent water building up within the shafts (kaneem) as they were searching for copper, they made this water runs off through an excavated (sareem) horizontal tunnels. Consequently, adjacent farming communities might have used the discharged waters. The farmers faced two barriers, first was the seasonal rivers, which have no water during dry and hot season. The second was the springs that drained shallow ground water and fell dry during the hot season. These farmers then established a relationship with the miners and asked them to dig more tunnels in order to supply more water even during the dry season to expand their farmlands (Yazdi and Khaneiki, 2010). Though some researchers are skeptical about the theory, there were strong possibilities for such a motivation. In this manner, the ancient Iranians made use of the excess water that the miners wished to dispose of and found a basic system named qanat to supply the required water to their farmland.

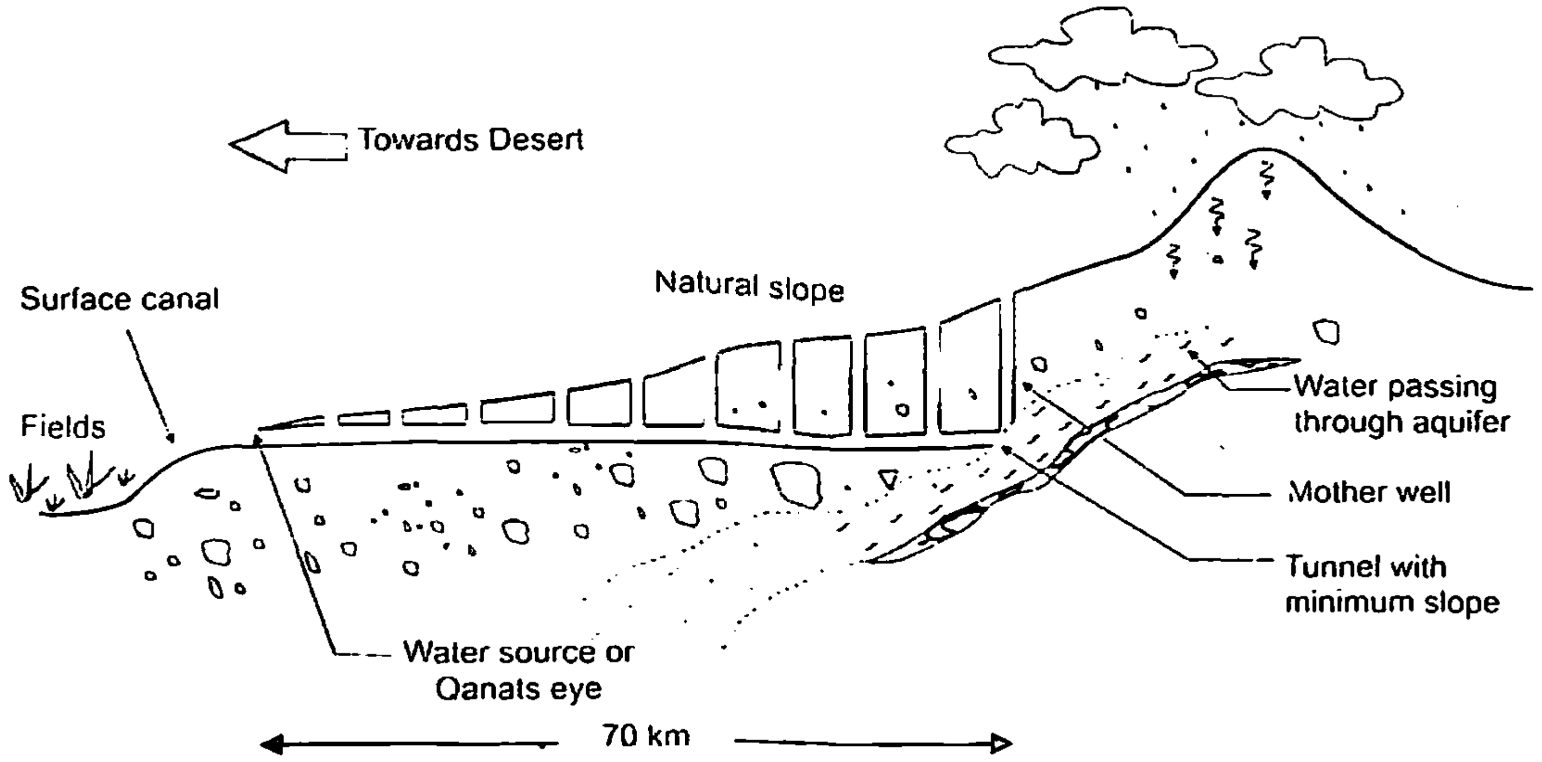

Fig. 8 Qanats system and associated features (Modified after www.learn.londonmet.ac.uk/.../ Qanats.html).

On the contrary, Yazdi and Khaneiki (2010) considered that the natural springs led the villagers to construct the first qanat. According to them, it is very likely that an ancient villager would be inspired by a trickling spring and excavated back to get closer to the source of water. Probably that was how the system of Qanats came into existence. Yazdi and Khaneiki (2010) witnessed similar process in an off the beaten path village in southern Khorasan. There was a natural spring in this village with a discharge of about 3 liters per second.

After a drought broke out, the water of this spring dramatically decreased, so that the villagers excavated the spring horizontally up to 30 m to reach for water. Subsequent years, they extended this tunnel to keep the discharge steady. After 20 years, that spring was turned into a qanat with two shaft wells. This is another scenario associated with building Qanats, which might be challenging the theory that miners of Urartu invented the Qanat as a byproduct (Yazdi and Khaneiki, 2010).

By any means, the historical evidences indicate that the innovation may have been taken place in Urartu and later was introduced to the neighboring areas. According to an inscription made by Sargon II the king of Assyria, in 714 BC, who invaded the city of Uhlu lying in the North West of Uroomiye lake that lay in the territory of Urartu empire (Assyrian term for the geographical region rose by iron age), indicates the presence of qanat (Laessoe, 1951). The Romans (64 BC to 330 AD) and their eastern Roman empire successors, the Byzantines (330-630 AD) gave to Jordan (and Syria) a great number of aqueducts and wells; they improved irrigation techniques in the region and expanded arable land, and it was during the centuries of Roman supremacy that the Levant entered upon a period of unsurpassed prosperity (Luke and Keith-Roach, 1930).

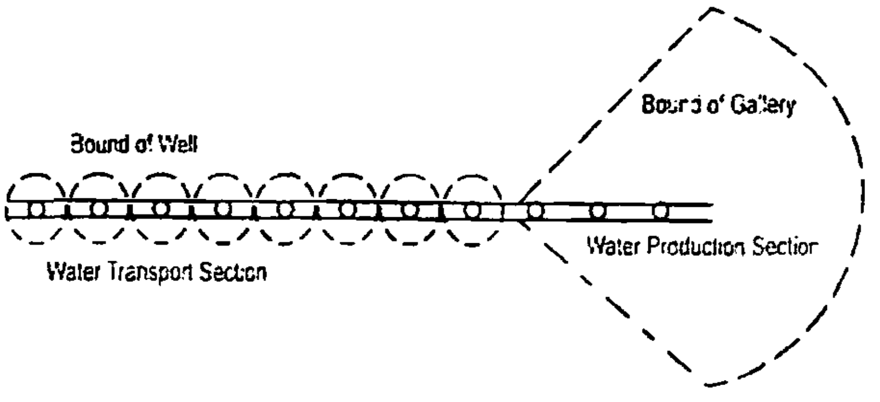

Fig. 9 Bounds of Qanats discribing hydrodynamic influences associated with wells and water production zone (After Yazdi and Khaneiki, 2010).

MODELS FOR QANATS

Qanats system has two important bounds one starting from effective mountain areas and the other along with the system of wells (Figure 9). Those bounded areas are subjected to hydrodynamic characteristics of the aquifer. Therefore, these areas are confined to a zone, beyond which the Qanats drainage has no impact on the water table (Yazdi and Khaneiki, 2010).

1). Bound of the qanat gallery

The bound of a qanat confined to both sides of the tunnel means a particular distance from every point of the tunnel exit to where the water percolation in to the tunnel has almost no impact on water table. The area of the qanat bound is at its maximum around the mother well and tends to be zero near the well between the water transport and the production sections.

2). Bound of a shaft well

This is an area around the well mouth, which is regarded as restricted to better protect the access well. The diameter of this area is determined by a traditional method named as Kolang-Andaz. In the past, this distance was usually considered 6 m.

There is another concept revolving around the bound of Qanats, wells and springs, called hydraulic bound. This bound refers to the area around the water source in which the water source can be affected hydraulically. In this area, no water mining system should be built. This bound is very controversial and is usually defined by constant number depending on the water percolating area but usually extended up to 1000 m. The hydraulic principles as applied to this system has not been touched in detail though evidences indicate that significant technical inputs were laid behind the Qanats technology (Yazdi and Khaneiki, 2010).

CLASSIFICATION OF QANATS ACCORDING TO THEIR BOUNDS

Qanats can be classified into two major types, viz; mountainous and plain. A semi mountainous Qanats can also be found in some cases.

1). Mountainous Qanats

In mountainous Qanats the reserved groundwater is actually tapped through a conduit created by seasonal rainfall. It is even possible that a particular qanat is fed by two separate conduits at two different points. In this case, it has adversely affected to the qanat to drill a well upstream from the qanat. Therefore, the designer should consider this issue while determining the qanat bound. However, one can allow another qanat just downstream from the first qanat, since taking water from the downstream conduit has nothing to do with the first qanat discharge. The bound of such Qanats correlate with the geological conditions and the positions of the subterranean conduits and their distance from each other, and in summary, their bound is not that large.

2). Plain Qanats

The bound of plain Qanats is larger than that of mountainous Qanats. The groundwater reserve on which the plain Qanats are dependent on is an integrated hydrological unit over the plain. Therefore, extracting water at any point in the plain can affect the discharge of the surrounding Qanats. In such case of Qanats drilling, a pumped well in downstream or upstream may cause qanat discharge to dwindle. Therefore, we should determine a bound for these Qanats so that the Qanats are affected as little as possible.

DISCUSSION

Several points of significant interest to compare the Qanats and TC irrigation systems will be discussed with their Physical, Biological, Social frameworks and linguistic lineage as follows. Some major similarities and differences will be addressed as identified in both these systems, however, extensive review of these systems are beyond the scope of this paper.

PHYSICAL FRAMEWORK

Physical setup of an irrigation system is the main platform for an effective water management planning process. Even in the ancient systems, the physical features were readily taken as the prerequisite for effective planning and designing of an irrigation system. After examination of qanat systems, Lightfoot (1996) explains the following general observations. Since Qanats tap into shallow aquifers - in alluvial fans or synclinal (down-folded or basin-shaped) rock beds - at the base of hills or mountains, or along the margins of larger wadis (stream channels) coming out of the mountains, there is a close relationship between Qanats and upland topography. All of Jordan's Qanats were constructed within the piedmont zone, mostly at elevations of 460 to 915 m, with the exception of the Qanats at Ma'an, which lie only 10 kilometers from a high range of hills and tap into aquifers fed from those highlands. Where groundwater is available farther from the uplands, it tends to be brackish and otherwise of poorer quality than water found in or very near the mountains. Therefore, the uplands supply Qanats with both a greater quantity and better quality groundwater, and these were never built beyond the montane (mountain area) piedmont zone. On the contrary, TCS tap into excess runoff flowing over rolling topography extended from the mountainous highlands. The tanks along the cascade act as temporary storage for flowing water. There is a close relationship between number of tanks and the rainfall regime (Gangadhara and Jayasena, 2005). Since groundwater available in the dry lowland areas, tends to be saline than water found in or very near the mountains (Jayasena et al., 1993), TCS supports additional relief to the community by providing potable water closer to the tanks. However, within the lower part of the NW drainage basins; the "wew" are not present indicating accumulation of bad quality water (Tennakoon, 2000). Table 2 shows water quality parameters of rivers, tanks and bore wells in Sri Lanka with that of Qanats in the Middle East.

Similar to Qanats, as one of the most widespread irrigation systems in arid tropical and subtropical lands, the TCS is a unique hydraulic system built in the dry zone of Sri Lanka. Square or round shapes of the Qanats at some sites in Jordan are cut into a thick limestone bed to depths of 10 to 60 meters with varying lengths from 1 to 6 kilometers where many Qanats are found when limestone exposed at the surface (Lightfoot, 1996). Similarly, the irrigation being practiced along with limestone bearing Miocene belt in the dry zone of Sri Lanka usually by "Andia" (Shaduf Shaft) wells dug through the formation physically resembles irrigation in the Qanats bearing parched lands in Iran. The wells are known as Andia wells (Shaduf Shaft) which tapped the groundwater similar to Qanats, however, operated by manually lifting water rather than diversion through underground man made channels. The aquifer is limestone analogous to the aquifer providing water to Qanats.

A recent finding in Wanathawillu in the northwest Sri Lanka, further supported such construction by inserting terra cotta cylinders akin to building shafts along with the qanat system (Priyankara, 2014). The terra cotta cylinders prevent soft soil collapse while facilitating the digger to proceed through the shafts with minimal danger. Both the Qanats and Andia well (Shaduf Shaft) bearing regions are subjected to sub aerial weathering of limestone where surface drainage seems meager. Except for Andia wells (Shaduf Shaft) as used for irrigation in the northwest Miocene belt, the crystalline terrain having very low primary porosity is irrigated by "wew (surface tanks)" riddled throughout the dry zone areas. Waters percolate to recharge the andia wells (Shaduf Shaft) either from the fractures connecting solution cavities in the miocene limestone belt or by limited rainfall of less than 500 mm annually received in the northern region of Sri Lanka. Therefore, practically there is no need for a subsurface network of tunnels as in Qanats since the water level is shallow and lifting mechanism is not difficult. On the other hand, limestone-bearing belt is confined to low plain along the coastal areas of Sri Lanka, which is quite different from the limestone exposed in mountainous terrain as seen in areas underlain by with Qanats.

Qanats depend on the groundwater in regions with very low annual rainfall. Most of the Qanats in Jordan (twenty-two of thirty-two galleries) were constructed in semi-arid regions receiving 100 to 300 mm average annual precipitation. This reflects the pattern in Iran and Syria, where major qanat systems are recharged through average annual precipitation ranges from 100 to 300 mm per year to 400 to 500 mm respectively (Lightfoot, 1996). The TCS received average annual rainfall in the range of 635-1250 mm. Most of the TCS in Sri Lanka were constructed in semi-arid regions receiving average annual precipitation less than 1250 mm. Therefore, in general, the arid areas of Sri Lanka receiving rainfall less than 635 mm and wet regions receiving rainfall greater than 1250 mm were excluded from constructing TCS (Manchanayake and Madduma Bandara, 1999).

Qanat system can be considered as a parallel system related to the TCS, however, major contribution of water would depend on the rainfall regime. After production and transport through the qanat, the water is directed through

Table 2 Composition of the water of the Qanat compared to the water from several sources in Sri Lanka and WHO drinking water standards for the developing countries.

Parameter	Units	*DO*[1]	*FP_MR*[2] *TW*	*Nik_RK*[3] *TW*	*Jaffna*[4] *Andia*	*Tanks*[5]	*WHO*[6]	*Qanats*[7]
Alkalinity, total	mg/l $CaCO_3$	*275*	*76.5*	*454*				
Hardness, total	mg/l $CaCO_3$	*250*	*47*	*345*	*504*	*91.6*	*500*	
EC	µS/cm	*1000*	*1400*	*1700*	*2500*	*422*		*850*
Calcium	mg/l	*64*		*61*		*21.00*	*50*	*58.12*
Magnesium	mg/l	*22*		*47*		*17.3*		*27.34*
Sodium	mg/l	*118*		*168*		*28.75*	*175*	*91.9*
Potassium	mg/l	*ND*		*68*		*3.67*		*1.95*
Iron, total	mg/l Fe	*ND*	*2.02*	*0.4*		*1.9*	*0.4*	
Chloride	mg/l	*170*		*234*	*584*		*400*	*107.77*
Bicarbonate	mg/l	*226*		*554*				*170.86*
Nitrate	mg/l NO_3	*9.2*	*0.24*	*0.27*		*0.7*	*50*	*26.04*
Sulfate	mg/l SO_4	*0.4*	*10.08*	*37*		*3*	*500*	*114.31*
Phosphate	mg/l PO_4	*ND*				*0.02*		
Fluoride	mg/l F	*ND*	*0.31*	*ND*			*1.5*	
pH		*7.6*	*6.83*	*7.2*	*7.3*	*7.15*	*6-8*	*8.2*
Turbidity	FAU	*52*	*11*				*5 (NTU)*	
Colour	ptCo-	*189*	*80*	*143*			*15 (TCU)*	

DO = Deduru Oya; TW= Tube Well, FP = Flood Plain; MR= Mahaweli River; Nik= Nickeweratiya; Rk = Rock, WHO = World Health Organization, ND = Not Detected
1&3. Singh and Jayasena, 1984, 2&5. Mahatantila et al., 2004; 4. Balendran, 1970, 6. Solsona, 2002, 7. Hoogeveen and Zöbisch, 1999.

a small open canal (*saqeh*) running through the village and collected in a reservoir (*birkeh*) at the end of the open canal. The *birkeh* can be opened and closed for irrigation from an outlet closed off with stones and cloth (Wessels and Hogeeveen, 2002). In TCS rainfall collection in the reservoirs (*wewa*) and subsequent transfer through canals is seen. The valve pit (*bisokotuwa*) provides the controlling mechanism for the irrigation requirement (Brohier, 1935).

Similar to Qanats, the TCS is also based on the simple technology of utilizing gravity to channel water from foothill areas to agricultural lands and settlements in lowland areas. The gradient along some of the artificially constructed channels joining large wew maintain a healthy 1:10000 slope with a winding and meandering pathways (Dharmasena, 2010), whereas Qanats maintained 1:1000 to 1:1500 slope along with a more or less straight or tangential pathways. In this way, the erosion could be minimized while the physical water quality could be maintained at a potable water quality. Moreover, within the TCS, natural stream flow along the surface drainage patterns is collected by intermittent embankments across shallow valleys, whereas within Qanats, groundwater is accessed through a chain of shafts and conveyed by a network of horizontal narrow underground tunnels. However, the scale seems large enough to cope with bigger discharge. In this context, both the Qanats and the Tank Cascade system are considered as the most efficient systems to provide cheap and safe water to the communities of the arid or tropical dry lands respectively (Wessels and Hoogeeveen, 2002; Jayasena and Selkar, 2004).

SOCIAL FRAMEWORK

The irrigation practices in the ancient hydraulic civilizations were endowed with strong social network. Regimes that are more powerful were emerged around tropical and subtropical areas where water becomes central theme for good governance. Extensive spread of Qanats was such outcome in these regions. Qanats provide water through subterranean canals as far back as five to six thousand years before the known history of Iranian decent exposed (Issar, 2002). A system of qanats was built by the Romans and used by the Byzantines from the 1st century BC (64 BC to 330 AD) to the 7th century AD (330-630 AD) (Luke and Keith-Roach, 1930). Not only are Qanats relics of a prosperous past, but also sustainable and environmental friendly system of extracting groundwater (Wessels and Hogeeveen, 2002). The ancient Sinhalese built TCS with stages extended from 3rd century BC to 11th Century AD. An uninterrupted sustainable water management for a period of more than 1500 years was portrayed in this historical period (Jayasena and Selker, 2004). The peak stages are the introduction of "Chulasammatha" or large tank system with valve pit at a later period to cope with water supply to large irrigation areas (Panabokke, 1999; Gangadhara and Jayasena, 2006). However, the extensive Qanats irrigation system built by Romans has not survived throughout the history except for a period of 7 centuries. It is also a result brought about by the change in the political regime possibly causing interruption of the maintenance, which leads to virtual abandonment. The indigenous knowledge of geology, hydrogeology and leveling based on flow associated with Qanats seems comparative to the system that had been operated in Sri Lanka.

Human settlements are depending on the availability of water. Several accounts associated with Qanats construction and human settlements can be revealed from literature (Shiraazi et al., 2012). Reifenberg (1955) state that the settlement in Jordan, even in mountainous regions with their more abundant rainfall, is possible only near springs and wells where provision is made for storing winter rains. It is further stated that, factors other than rainfall alone must account for the existence of Qanats. For example, north west Jordan is the most heavily and permanently settled area by Romans, since it is contiguous to the more humid and is one of the most favorable areas in Jordan for constructing Qanats with regard to the suitability of aquifers (Lightfoot, 1996). In Sri Lanka, settlements in lower plains are far higher even in the ancient periods, which may be lined up with the efficient TCS and associated trade centers. Even during difficult political history starting from 12th century onward, the settlements seem quite high with major townships, however, gradually diminishing in the rural areas underlain by TCS. In the mountainous uplands with their more abundant rainfall, human settlement was associated with spice trade and paddy cultivation, whereas, in the mountainous highlands, the population seems low (Jacob and Alles, 1987).

Maintenance of irrigation systems through local community participation is imperative for efficient water management. Traditionally, Qanats should be cleaned on a regular basis to prevent silting, collapsing and disfunctioning. This helps keeping the qanat flowing even in dry seasons (Wessels and Hogeeveen, 2002). Similarly, tanks and conveyance canals associated with the TCS should be cleaned and maintained on a regular basis to prevent silting tank beds, piping and collapsing bunds and disfunctioning "bisokotuwas". In turn, such regular maintenance provides continuous subsistence paddy farming without any interruption, which led to survival of the TCS throughout history. With the abandonment of Qanats, the indigenous knowledge and community co-operation critical for qanat upkeep also disappears. This in turn leads to more Qanats collapse or dry up. As a result, a valuable cultural heritage is vanishing. Similar outcome was resulted after 11th century AD when the abandonment of the TCS leads to deteriorate the indigenous knowledge and community co-operation critical for its upkeep. However, this valuable cultural heritage was not totally vanished from the community, even with 7 centuries of political unrest. Not only are the tanks indicate of a prosperous past, but also expresses their sustainability and environmental friendly systems of harnessing surface runoff for socially driven efficient water management within the dry zone (Tennekoon, 2000; Jayasena and Selker, 2004).

In modern times, Qanats are not able to provide enough water for large-scale agriculture and therefore, loose their importance (Wessels and Hoogeveen, 2002). However, the TCS can still provide sufficient irrigation water to the dry zone farmer. Especially after 19th century when the British Colonial rulers revamped the Tank Cascade System, the effectiveness of the irrigation operation was evident and sustainable even with the current global, social and economic transformation (Jayasena and Selker, 2004). The agricultural practice has undergone drastic changes due to modern transformation, which readily affected in some parts of the world where such irrigation systems are practiced. In fact, these systems have either gone into decline or stopped functioning completely. Therefore, it is necessary to design a plan of action to rehabilitate these systems and to improve their potential. Further, it is important not only to unravel the technologies behind Qanats and the TCS but also to see how these systems could survive under the present demographic framework.

Strong social cohesion in a community is a condition for effective management of any irrigation system, whether Qanats or the TCS as a common water resource. It should be noted that social cohesion differs and should be studied on a case-by-case basis. In the Arab rural areas, a strong village or family leader is usually a condition for good social cohesion. The users' community is a well-organized body in such traditional system of "water committees" and "water guards" supervised by the farmers' cooperative societies (Wessels and Hogeeveen, 2002). Guidance by a Village leader was a condition for any management of the TCS as well, since the tank water was a common source for irrigation. It should be noted that social cohesion was more uniform in the ancient hydraulic civilization. In rural areas, a strong village or family leader (*Vel Vidane*) usually guides for good social cohesion. Even in Sri Lanka, the users' community was well organized in a traditional system of "water allocation meetings" supervised by the Vel Vidane (Jayasena and Selker, 2004; Aheeyar, 2000). However, one need to scrutinize the current situation to address the validity of such condition with the modern irrigation practice within the TCS.

AGRICULTURAL (BIOLOGICAL) TERMS

Villagers use qanat water to irrigate a community garden (*bustan*) to grow food crops such as onions, cucumbers, tomatoes and other vegetables for additional nutrition of the households. The garden also contains fruit trees such as mulberry, figs and pomegranates. In addition to that, they grow irrigated barley to provide feed for the sheep (Wessels and Hogeeveen, 2002). In Sri Lanka, the villagers use wew water to flood irrigate paddy fields. The herbs grow in the upper periphery (*thaulla*) of the Wewa supply with the medicinal requirements of the villagers. In addition, they grow vegetables along the mounds separating paddy lands and paddy trashing areas for a sustainable life within a closed system. As Lightfoot (1996) finds in the Qanats irrigation practice, sedentary agriculture can prosper only during periods of efficient and stable government. This is further evidenced by agricultural output portrayed as prosper during periods of efficient and stable government in Sri Lanka which span approximately for a period of 1500 years (Jayasena and Selker, 2004). Since sustainability of the dry zone agricultural society depends on factors such as efficient irrigation water management and healthy work force supplemented with fresh food and good quality drinking water, the water quality for irrigation systems, rivers, wells and flood plains of several regions in Sri Lanka was examined and compared with that of Qanats. The comparison indicate that the water quality parameters are within the limits of WHO standards. The groundwater channeled through Qanats show similar water quality parameters as with surface flow along the Deduru Oya.

LINGUISTIC LINEAGE

It is interesting to note that the term "Kanim" has been used for digging wells, or mining metals and gems in Sri Lanka, which has a similar notation as "Kane" in Persia (Yazdi and Khaneiki, 2010). Even in Jordan, people used two different terms for the Qanats; kaneh in Northern Jordan while sarab in the southern Jordan. Again these two terms are somewhat related to digging (kanim) and excavating (Sarim) as used in Sri Lanka. Whether it is pure coincidence or a technology transfer during pre-Mahawansa era is a question to be pondered by the historians, however, the common meaning is well established.

REMARKS

1. Ancient hydraulic civilization was not only confined to a particular country, but it has been established, evolved and extended throughout the tropical and subtropical regions depending on local hydrologic, geologic and social condition.
2. Sustainability of ancient hydraulic civilizations were centered on good governance, however, change in the political regime cause interruption of the maintenance, leading to virtual abandonment of such irrigation systems. Therefore, strong social cohesion within the community is a prerequisite for effective irrigation management.
3. Both the Qanats and the TCS have many similarities in their hydraulic behavior morphological setup, aerial distribution, sociotechnical inputs, social cohesion including motivation for regular maintenance, linguistic lineage and irrigation output except the geology and the rainfall distribution. However, a major difference is that Qanats deal with groundwater while the TCS deals with surface runoff.
4. The Qanats system though seems to have problems at present, could be revamped by making necessary policy decisions while implementing changes according to a systematic plan. On the country, the Sri Lankan scenario is different since the functioning of the TCS has been revamped for productive output.
5. To cope with the longevity and proper functioning of the TCS, construction of tanks and settling human habitats in the dry zone of Sri Lanka had been conducted in a technical manner, considering pure sociotechnical criteria (Jayasena, 2012). Both the Qanats and the TCS are operated based on the simple technology of utilizing gravity to channel water from foothill areas to agricultural lands and settlements in lowland areas. Effective planning and designing of the TC or the Qanats irrigation systems, therefore, depend on the gravitational flow of orographic rainwater either over the landforms or through the landmass respectively.
6. It is clear that the waters from the Qanats behave chemically similar with waters used for irrigation in Sri Lanka. The comparison also indicates that the water quality parameters are compatible and within the limits of WHO standards. Even in those desert areas, the Qanat technology provide very useful mechanism to control evaporation and minimize salt accumulation to stand with water quality sufficiently acceptable for prosperous agriculture practice.
7. The findings discussed in this paper favored mining based groundwater discharge mechanism as responsible for the development of Qanats, rather than random approach of extending the galleries to fetch water.

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