Qanats and Lifeworlds in Iranian Plateau Villages

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ABSTRACT

Through a review of the literature on *qanat* history, this article provides an overview of one of the most significant hydraulic technologies of the pre-modern Middle East. The article covers *qanat* origins, diffusion and construction techniques, then compares the productivity and sustainability of *qanats* with modern deep well systems powered by motorized pumps. The replacement of *qanats* with deep wells has serious implications for the ground water resources of much of the Middle East. The profound importance of *qanats* in shaping the lifeworlds of villagers in pre-modern Iranian plateau settlements has meant that the shift towards reliance on deep well systems has had ramifications for plateau society that go far beyond water resource exploitation.

INTRODUCTION

Throughout the arid Middle East and North Africa, water shortages have become increasingly acute. Population growth combined with agricultural expansion and intensification have heightened demand for domestic, industrial, and agricultural (especially irrigation) water use. Local surface and subsurface water resources are no longer sufficient to meet these burgeoning needs throughout the region. Domestic water is in such short supply that it is rationed in a number of Middle Eastern cities, and, as the region's cities continue to grow, it is likely that urban water demand will also grow. In rural areas, irrigation water is increasingly scarce. A scarcity of irrigation water will force small farmers off the land and increase food imports across the Middle East.

Domestic water is in such short supply that it is rationed in a number of Middle Eastern cities, and, as the region's cities continue to grow, it is likely that urban water demand will also grow.

To meet growing demands for water, governments and other investors in the Middle East have abandoned traditional, sustainable (but less productive) water supply systems in favor of modern, less sustainable (but more productive) hydraulic systems. In river valleys, modern dams have been constructed to trap surface water. Where surface water is not available, modern pumping technologies that provide access to previously unknown or inaccessible groundwater reservoirs are coming into widespread use.

One of the most striking example of this shift in water technologies has been the case of *qanats.* These ancient, gravity-flow water supply systems, which have provided dependable, renewable supplies of water to Middle Eastern towns and villages for millennia, are being rapidly replaced by a more productive but less sustainable water technology, deep wells. On the Iranian plateau, an important heartland of *qanat*-watered settlement, this change in water technology is draining aquifers, altering the distribution of towns and villages, and transforming the lifeworlds of Iranian villagers.

QANATS AND SETTLEMENT IN THE OLD WORLD

THE NATURE OF *QANATS*

Qanats are gently sloping subterranean tunnels dug far enough into alluvium or water-bearing sedimentary rock to pierce the underground water table and penetrate the aquifer beneath. Water from the aquifer filters into the upper reaches of these channels, flows down their gentle slope, and emerges as a surface stream of water at or near a settlement. *Qanats* are generally constructed on the slopes of piedmont alluvial fans, in intermontane basins, and along alluvial valleys. In these locations, this groundwater collection system has long brought water to the surface and supported settlement in regions where no other traditional water technology would work.

Most of these gravity-flow tunnel-wells are relatively short, some five kilometers or less in length (Beaumont l989). The longest, however, extend 40 or 50 kilometers beneath ground level before surfacing at a settlement (English l966). The cross section of a *qanat* tunnel is roughly one-and-one-half meters high and one meter wide, large enough to accommodate men working. Every 50 to 100 meters or so on the surface, vertical shafts are dug down to a depth of anywhere from 10 to 100 meters to the water-bearing tunnels. These shafts provide air to *qanat* diggers working beneath the surface and also enable excavated soil to be removed from the tunnel and lifted to the surface. The shafts provide repair teams with relatively easy access to tunnels when blockages occur. The donut-shaped spoil heaps around the tops of these vertical shafts appear on the surface as a chain-of-wells, a distinctive feature of landscapes in *qanat*-watered regions. These markers chart the subterranean pathways of the *qanat* tunnels (English 1968; Beaumont 1971; Goblot 1979).

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ORIGINS AND DIFFUSION

Qanats first appeared in the mountains of Kurdistan in western Iran, eastern Turkey, and northern Iraq more than 2,500 years ago in association with early mining in that region. Several factors explain this origin. Most importantly, perhaps, this region is one of the oldest mining and metallurgical centers in the Middle East. The need to dig tunnels in the search for minerals meant that the inhabitants of the region had mastered the basic technology necessary for *qanat* construction. *Qanats* differ little from the horizontal adits dug into hillsides by early miners. Indeed, these adits may well have been sloped to drain unwanted seepage as they are today. Additionally, and somewhat ironically, the earliest report of a *qanat* system is chronicled on a tablet narrating the destruction of the *qanats* which provided water to the city of Ulhu (modern Ula), located at the

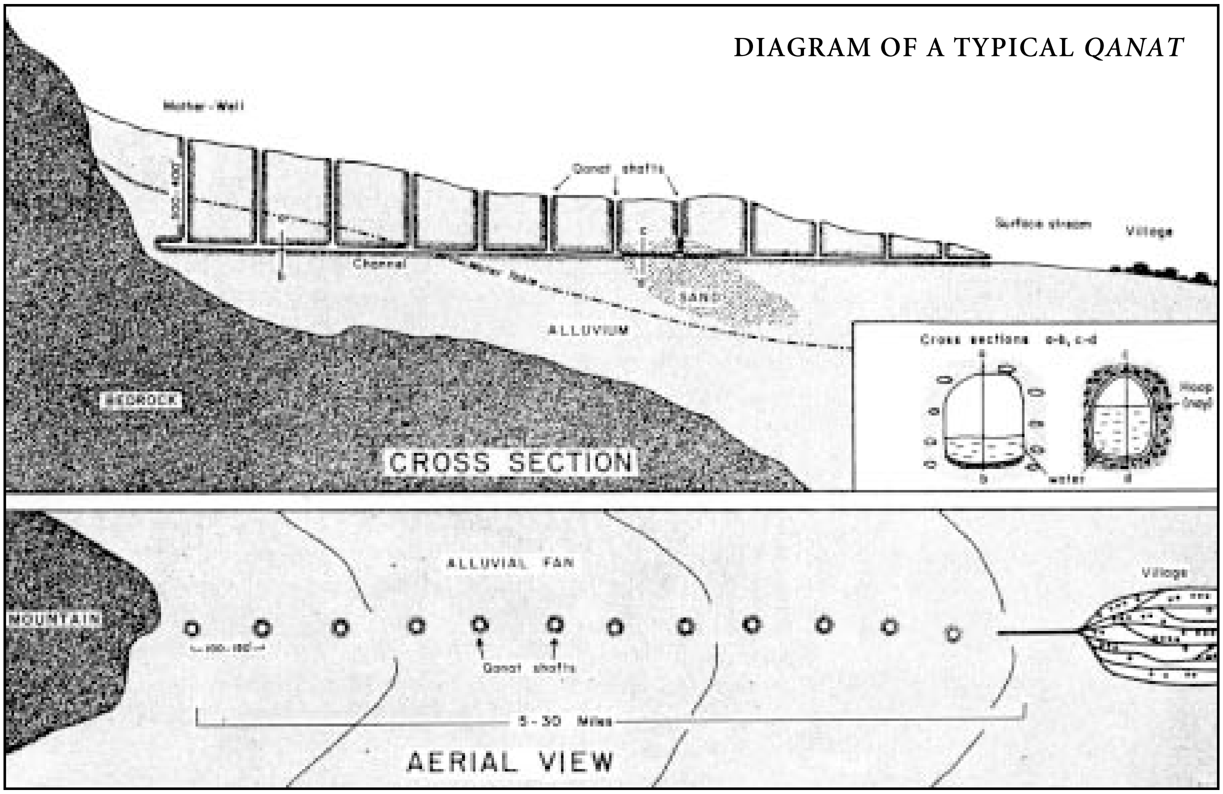

Figure 1 **Cross Section and Aerial View of a *Qanat*.** *Qanats* are ancient water supply systems constructed using a simple technology. The vertical shafts are not "wells," despite the term "chain-of-wells" often used to describe their appearance on the landscape.

northwestern end of Lake Urmia by Sargon II in 714 BC (Laessøe 1951). Soon thereafter, Assyrian cities, particularly those located on the upper Tigris River, relied on *qanats* for drinking water. Somewhat later, the capital city of the Medes, Ecbatana (modern Hamadan) was watered by qanats as was Darius's capital city of Persepolis (Forbes 1955; Goblot 1963).

Under the Achaemenids (550–331 BC), when Persian rule extended from the Indus to the Nile, *qanat* technology spread well beyond the confines of the Iranian Plateau. The Achaemenid rulers provided a major incentive for *qanat* construction by allowing *qanat* builders and their heirs to retain profits from newly-built *qanats* for five generations. As a result, thousands of new settlements were established and others expanded. To the west, *qanats* were constructed from Mesopotamia to the shores of the Mediterranean as well as southward into parts of Egypt and Arabia. They were particularly important sources of water in the foothills of eastern Iraq, the Syrian Desert, and the Hadhramaut. In the Yemen and in Oman, *qanats* are locally called *falaj* (plural: *aflaj*).

To the east of Iran, where they are generally known by the Persian term *kariz*, *qanats* came into use in Afghanistan, the Silk Road oases settlements of Central Asia, and the Chinese province of Sinkiang (now Xinjiang), although whether this diffusion occurred under the Achaemenids or some later Persian dynasty is uncertain. Strangely, in the Turfan Basin, which has one of the most extensive *qanat* systems in the world, it is possible that many of the *qanats* were built by imported Turki laborers in the 1700s (Stein 1933).

The expansion of Islam initiated a second major diffusion of *qanat* technology. The early Arab invasions spread *qanats* across North Africa into Spain, Cyprus, and the Canary Islands. In most of North Africa, they were called *fughara*, and were built and maintained by a specialized caste of black slaves. In Morocco, *qanats* were referred to as *khittara* (or *rhettara*).

Qanat use was especially intense in three areas of the Maghrib: on the borders of the Tademait Plateau just south of the Great Western Erg in central Algeria; on the northern slopes of the Atlas Mountains of Morocco, particularly near the city of Marrakech; and south of the Atlas in the Tafilalt of Morocco (Fenelon 1941; Lo 1953; Margat 1958). Interestingly, *qanat* technology may have been introduced into the central Sahara and later into Western Sahara by Jews or Judaized Berbers fleeing Cyrenaica during Trajan's persecution in AD 118 (Briggs 1960).

Because qanats *could provide reliable and sustainable access to previously unavailable supplies of groundwater, populations throughout the arid zone embraced their use, despite the cost in money and time to build and maintain them.*

In Spain, *qanats* were used marginally in the province of Catalonia and at Madrid where they were called *gálerias* (Asin 1959: Plate XVII). They are important sources of water in Cyprus and on Gran Canaria and Tenerife in the Canary islands (Humlum 1965).

New World *qanats* are found in Mexico at Parrás, Canyon Huasteca, Tecamenchalco, and Tehuacán and in the Atacama regions of Peru and Chile at Nazca and Pica. The *qanat* systems of Mexico came into use after the Spanish conquest; those of the Atacama, however, may predate the Spanish entry into the New World (Kaeger 2, 1901; Troll 1963).

QANAT CONSTRUCTION

The spread of *qanats* throughout the arid lands of the northern hemisphere during the pre-modern period may be explained by the fact that they use an efficient mix of available capital and technology to supply critically scarce water. Because *qanats* could provide reliable and sustainable access to previously unavailable supplies of groundwater, people throughout the arid zone embraced their use, despite the cost in money and time to build and maintain them.

During much of the pre-modern period, many *qanat* systems were built by powerful political leaders, whose rule was often

Figure 2 **A *Qanat*-fed Alluvial Fan Village.** A detailed understanding of subtle variations in topography, landscape, and subsurface water conditions is required in the siting of a *qanat*. Only well-known and respected *muqannis* are entrusted with site decisions. *(Illustration by Ann Coffin Delano)*

appraised by the number of *qanats* constructed during their reign. For example, slaves and captives were trained to construct *qanats* under the Achaemenid and Sassanian kings. Maintenance and repairs were accomplished by corvée (forced labor).

THE *MUQANNIS*

More recently in Iran, a hereditary class of professional *qanat* diggers called *muqannis* build and repair these systems. These specialists travel from place to place on the Iranian plateau, for example, working at one settlement where a flash flood has damaged a *qanat*, and then moving on to another where a lowered water table requires that a *qanat* tunnel be extended deeper into the alluvium.

The most famous *muqannis* come from the desert city of Yazd. They are paid high wages, and command respect. The hazardous nature of their work has inspired a body of folk custom and belief. A *muqanni* will not work on a day he considers to be unlucky, or if he sneezes on that day. Floods and cave-ins in the *qanat* tunnels are frequent, and deaths among *muqannis* occur. Older *muqannis* are considered blessed or at the very least lucky. Prayers are said over a *muqanni* each time he descends into a *qanat*, a ceremony that makes a deep impression on Iranian villagers.

SITE, GRADE, AND ALIGNMENT

The construction of a new *qanat* (which is quite rare at present) is a sophisticated engineering feat accomplished with simple tools. The success of the undertaking is determined by two decisions made by a *muqanni* before the actual construction of the *qanat* begins. The first of these is to determine the site of the "mother well" (*madari chah*) which marks the furthest extent of the *qanat* from the settlement; the second is to establish the alignment and grade between the *qanat's* origin and destination.

When the *muqanni* decides on a potential site for the *madari chah*, one or more trial shafts (*gamaneh*) are dug deeply enough to penetrate the water table. A variety of geographical factors are weighed in the *muqanni's* decision as to where these shafts are located. Among these factors are local slope conditions, the surrounding topography, subtle changes in vegetation, available groundwater, and the proposed destination of the water.

The many hazards that attend qanat construction have, not surprisingly, endowed the profession of muqanni *with a certain notoriety.*

Favorable site conditions for relatively short *qanats* often occur near the mouths of dry alluvial valleys. For long *qanats*, the general topographic setting is more indicative of the likelihood of accessible sources of groundwater. Once a trial shaft has struck water, the *muqanni* must be certain that this well has pierced the water table or alternatively has penetrated a relatively constant source of groundwater perched on an impermeable stratum. If so, this shaft becomes the "mother well" of the *qanat* whose length will be measured from this point to the place where water surfaces (*mazhar*).

Next, the *muqanni* must measure the precise alignment and grade of the *qanat* tunnel, the most difficult engineering task in the entire construction process. The alignment of the *qanat* must connect the water-filled base of the "mother well" with a point on the surface immediately above the settlement by means of a gently sloping tunnel. If the alignment is miscalculated and the *qanat* emerges some distance away from the settlement, water will have to flow in an open channel from this point to the houses and fields below, increasing both evaporation and seepage. If the gradient of the tunnel is too steep, water rushing down its course will erode the walls and collapse the *qanat.* If the gradient is too shallow, water will pond and stagnate in the tunnel. In many cases, the *qanat* tunnel follows an indirect, looping pathway to its destination, curving to maintain proper grade on steep slopes.

The maximum gradient for a short *qanat* is roughly 1:1,000 or 1:1,500. In a long *qanat* tunnel, the grade is close to horizontal. These calculations are made using a spirit level suspended between two pieces of twine each about 10 meters long (Beckett 1953: 48). Using only these tools, a skilled *muqanni* is able to determine both the proper alignment and grade of the *qanat* tunnel even when it runs for kilometers beneath rugged terrain.

EXCAVATION

The excavation of the tunnel starts in the dry, downslope section of the qanat at the *mazhar* and works back toward the "mother well." Vertical shafts connect the tunnel with the surface every 50 to 100 meters or so, as noted above. In some cases, these shafts are dug first, and the tunnel is constructed to connect their bases.

A team headed by a *muqanni* works together in the construction of a *qanat*. The *muqanni* excavates the tunnel with a small pick and shovel, while his apprentice packs the loose dirt into a rubber bucket (in earlier times a skin bucket). Two laborers at the surface haul the dirt up the shaft using a windlass (*charkh*). If the *qanat* tunnel reaches depths of 75 to 100 meters, a second windlass is set in a niche halfway down the vertical shaft and the dirt is transferred from one bucket to another at this point in order to facilitate the excavation process.

The greatest dangers in *qanat* construction occur when the tunnel reaches the wet, water-bearing section. Here, the *muqanni* and his apprentice work with water flowing around them, in poor ventilation, and with the constant threat of cave-ins. In some cases, vertical shafts fill with water before reaching tunnel depth. The *muqanni* must then dig upward from the tunnel to the pooled water in the shaft, and try to avoid the rush of water when the breakthrough is made. Where the tunnel passes through a deposit of soft sand and the tunnel is likely to collapse, baked clay hoops (*nays*) are inserted in the tunnel to provide extra support.

Figure 3 **Muqannis Excavating Soil from a Qanat Shaft.** Spoil lifted by windlass encircles the vertical shafts that link the qanat tunnel with the surface. Clearing blockage from qanat tunnels is usually required every few years.
(Illustration by Ann Coffin Delano)

Below ground, *muqannis* carry a castor oil lamp for both illumination and testing the quality of the air in the tunnel. If the flame dies for want of oxygen, the diggers know to leave the tunnel and dig another vertical shaft to provide more air. Where the *qanat's* tunnels are very deep and ventilation is particularly poor, vertical shafts are dug on either side of the tunnel. A fire is lit to make the stale air rise up one shaft and draw fresh air down the other (Noel 1944). In some areas, notably Yazd, twin *qanats* are built side-by-side, enabling *muqannis* to move from one tunnel to the other. The many hazards that attend *qanat* construction have, not surprisingly, endowed the profession of *muqanni* with a certain notoriety.

TIME AND COST

The time required to construct a *qanat* varies with the capital of the owner, the stability of ownership, underground soil and water conditions, the length of the *qanat*, the amount of water desired, the skill of the *muqanni*, and a variety of other social, economic, and environmental factors. In an alluvial fan village in Kirman, a *qanat* one kilometer in length with a mother well 45 meters deep was in construction for twenty-seven years, largely due to three changes in ownership. By contrast, a *qanat* in a similar location some three kilometers in length with a bifurcated tunnel and two mother wells 50 and 55 m in depth began to flow after seventeen years. The respective costs of these short, alluvial fan *qanats* were approximately $10,000 to $11,000 per km in the late 1960s (English 1966).

The cost of constructing a 40 km long *qanat* to the basin city of Kirman with a mother well 90 m deep was approximately $213,000 when completed in 1950. Given inflation, higher wages, the dwindling number of *muqannis*, and the political instability of modern Iran, the costs of building such a *qanat* today would likely be prohibitive. Confidence in future political and economic stability would have to be considerable to induce an investor to finance new *qanat* construction today.

The rate of flow of water in a qanat *is controlled by the level of the underground water table. Thus a* qanat *cannot drain an aquifer, because its flow varies directly with the subsurface water supply. When properly maintained, a* qanat *is a sustainable system that provides water to settlements indefinitely.*

QANAT TECHNOLOGY AND DEEP WELLS

Qanats were in wide use throughout the dry lands of the Old World until recently for several reasons. First, *qanats* are made of local materials. Second, they tap aquifers using no source of power other than gravity. Third, water is transported for substantial distances in these subterranean conduits with minimal loss of water through evaporation and with little risk of pollution. Water loss through percolation is reduced by lining the tunnels with clay hoops when they pass through loose sand, and by infusing their beds with layers of impermeable clay.

QANATS: WATER AS A RENEWABLE RESOURCE

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The self-limiting features of *qanats* that make them a sustainable technology can, however, be their biggest drawback, particularly when they are compared with the range of technologies available today. First, the flow of water in *qanats* varies from year to year depending on the recharge rate of the aquifer. In the Middle East, where drought hits on average once every four years, this uncertainty often results in conservative cropping strategies geared to the cultivation of low-risk, low water-consuming, low value crops like wheat and barley.

Second, water flows continuously in a *qanat*, and although some winter water is used for domestic use, much larger amounts of irrigation water are needed during the daylight hours of the spring and summer growing seasons in Middle Eastern villages. Although this continuous flow is frequently viewed as wasteful, it can, in fact, be controlled to a large degree. During periods of low water use in fall and winter, water-tight gates can seal off the *qanat* opening (*mazhar*) damming up and conserving groundwater for periods of high use. In spring and summer, night flow may be stored in small reservoirs (*ambar*) at the mouth of the *qanat* and held there for daytime use (Beaumont 1989). Moreover, much perceived seasonal water loss infiltrates the soil beneath the *qanat* tunnel and thus recharges the aquifer.

Third, the body of custom and law (*shari'a*) relating to *qanats* codified in the *Kitab-i Qani* (Book of *Qanats*) in the ninth century strives to protect the investment of *qanat* owners in permanent agricultural settlement. The law of *harim* (borders), for example, prohibits the sinking of new mother wells within one kilometer of existing *qanats*. As a result, large areas of land in the vicinity of cities like Tehran, Sulamaniyah, Yazd, Kirman, Herat, and Qandahar, where the density of tunnel wells is high, are closed to new settlement. This, in effect, stabilizes agricultural acreage in regions with growing populations (English 1966).

By far the major disadvantage (and advantage) of deep wells, however, involves their success in meeting the growing need for water in the Middle East. Deep wells can draw water from permanent aquifers on demand without regard to rates of recharge. The technology, therefore, enables people to exploit their water resources in an unsustainable fashion.

Again, the major limitation (and paradoxically the major advantage) of *qanats* is that their rate of flow is limited by the aquifer height. Should the water table fall during a drought, so will the amount of water filtering into the water-bearing section of the *qanat*. If the aquifer rises, the flow of water increases. This makes *qanats* a sustainable, renewable source of water, but it also makes them inadequate water producers *vis-à-vis* modern demands. The rapidly increasing demand for water generated by population growth and agricultural expansion in the modern Middle East cannot be accommodated by *qanats*.

DEEP WELLS: WATER AS A NON-RENEWABLE RESOURCE

By contrast, deep wells have several putative advantages over *qanats*. First, deep wells are not limited by slope or soil conditions and can be located at sites convenient to transportation networks, populations centers, and markets. Second, they draw water from deep in the aquifer where seasonal variations in flow do not occur. Third, because deep wells can be turned on or off at will, they are, theoretically, conducive to water conservation.

But deep wells also have disadvantages. The construction, maintenance, and fuel costs (for motorized pumps) of deep wells are high

(Overseas Consultants 1949). Moreover, deep wells cannot be built using local materials and local labor. By far the major disadvantage (and advantage) of deep wells, however, involves their success in meeting the growing need for water in the Middle East. Deep wells can draw water from permanent aquifers on demand without regard to rates of recharge. The technology, therefore, enables people to exploit their water resources in an unsustainable fashion. The ability of deep wells, and motorized pumps, to withdraw water in excess of an aquifer's recharge rate makes this modern technology very attractive in the short term. As a result, however, water is fast becoming a non-renewable resource in areas where deep wells are used.

QANATS AND VILLAGE LIFEWORLDS

Like all water technologies, *qanats* require a nexus of environmental and social conditions in order to be effective over time. On the Iranian plateau, reliance on *qanats* promoted high levels of social and ecological adaptation. They inspired a need for social cohesion that permeated virtually all areas of village life.

Qanats defined village lifeworlds on the plateau by (1) determining settlement location; (2) structuring built environments within settlements; and (3) requiring social cohesion in water allocation, water distribution, water use, and system maintenance. These lifeworlds framed the horizons of everyday life in plateau settlements, encompassing people's firsthand involvement with the practical world, the world of values, and the world of goods (Buttimer 1976; Seamon 1979). With the shift from *qanats* to deep wells, water-based social patterns are in flux.

WHERE PEOPLE LIVE

Qanat technology was known in Iran by the sixth century BC, when Indo-Iranians began to settle as agriculturists, to worship one god (Ahura Mazda), and to conquer the Old World. Three centuries later, when the Parthians invaded Iran, *qanats* were in widespread use on the Iranian plateau (Polybius X: 28; Vitruvius VIII: 6.3). By this time, *qanats* had opened alluvial fans to settlement, enabled basin cities to expand, and established the foundations of modern plateau settlement patterns.

Qanats became an important factor in where people lived. The largest towns were still located at low elevations on the floors of intermontane basins and in broad river valleys. Most of these early settlements were defended by a fortress (*qal'eh*) whose water was drawn from hand-dug wells that reached down to shallow water tables. *Qanats* enabled these settlements to grow by tapping waterrich aquifers located deep beneath neighboring alluvial fans. *Qanats* carried water from the fans below ground for many kilometers to such settlements providing supplementary water to irrigate more extensive fields and sustain larger urban populations.

Even more dramatically, *qanats* made it possible to establish permanent settlements on the alluvial fans themselves. Earlier settlers had bypassed the alluvial fans because water tables there were too deep for hand-dug wells, and the wadis on these slopes were too deeply incised in the fans for simple diversion channels. In these locations, *qanats* tapped somewhat more limited "water hinterlands" with underground water drawn from upslope alluvial deposits in mountain valleys. For the first time, small towns and villages were built at these higher elevations. And further up river valleys in the mountains, small *qanat*-watered hamlets appeared.

Figure 4 ***Qanats* Converging on the City of Kirman.** Built during the course of many centuries, large numbers of *qanats* converge on most Iranian Plateau cities. Some of these old *qanat* tunnels cross back and forth between channels, others are twin *qanats* one or both of which may be active, and many have been abandoned. No map of the resulting labyrinth of *qanat* tunnels is available. Note the differences in surface definition on the image caused by drifting sand.

In many areas, these water hinterlands formed a series of progressively smaller arcs with the *qanats* of each higher settlement starting where those of the next lower settlement ended. Although configurations varied on the plateau, frequently the regional settlement pattern exhibited a correlation in age, size, water rights, and elevation. The largest place was the oldest and the lowest, and usually had prior rights to the largest water catchment basin. In any case, over much of the Iranian plateau these new upland settlements increased the cultivated area, supplied additional food to urban centers, provided living space and work for a growing population of farmers, as well as upland bases for herders and fuel collectors.

The Iranian plateau was the first core area of intensive *qanat* use. Even today, as much as one third to one half of the irrigated fields and orchards on the plateau–an estimated 15 million acres–are still watered by *qanats*. Cities like Tehran, Qum, Qazvin, Hamadan, Nishapur, Yazd, and Kirman received virtually all of their water from tunnel-wells until deep wells were introduced after World War II. In the 1960s, an estimated 21,000 *qanats* were still functioning in plateau settlements with an additional 17,500 used but in need of repair (Ghahraman l958). Their aggregate length has been placed at more than 160,000 kilometers, and their total discharge at 20,000 cubic meters per second (Goblot l962).

Although these figures are not precise, they convey a sense of the scale of *qanat* use on the Iranian plateau, the role of *qanats* in defining the location of settlements, and their importance in the day-to-day lives of Iranian villagers. In more immediate ways, *qanats* defined the built environments of towns and villagers, the architecture of daily lives.

Figure 5 **A Water Divider in Mahan.** Two granite blocks were imported to Mahan to build a *maqsam* which subdivided the water emerging from two *qanats* into three major streams (*shahjub*) of equal flow. At some past time, one of the granite blocks was dislodged by a flash flood. Because of disagreement about its precise location prior to the flood, it was never repositioned. The owners of the major stream on the right clearly gained water because of the new position of the divider after the flood. The owners of the central stream lost water. Note that a third *qanat* enters the stream on the right below the *maqsam*.
(Illustration by Ann Coffin Delano)

THE BUILT ENVIRONMENT

The built environments of most alluvial fan towns and villages on the Iranian Plateau are aligned along the major watercourses (*shahjub*) that run from the mouth of the *qanat* down slope through the length of the settlement. In larger and more complex basin settlements, smaller streams of water emanating from the points of division (*maqsam*) of several *qanats* form a spatial skeleton of parallel pathways lined by village structures, walled orchards, and gardens. They are trunk lines of human activity.

Most alluvial fan settlements are triangular in shape. Below walled orchards and gardens at the top of the village, secondary distribution channels (*jub*) branch outward from the *maqsam* to form "water lattices" that broaden the area being cultivated. These smaller streams irrigate an elaborate grid of rectangular plots (*kort*) of irrigated land bounded by low, parallel levees (Bonine 1982; 1979).

The rectangular shape of these fields is designed to deliver the required amount of water to the *kort* by the time its flow reaches the plot's downstream end. Rectangular fields also assist in measurement of area at times of land subdivision, inheritance, or sale.

The linear constraints that *qanats* place on settlement morphology is most obvious in small alluvial fan villages, where a single watercourse runs downstream through the settlement providing water to each household compound, orchard, and garden before irrigating grain fields downslope. Each household compound has the right to water its courtyard garden and to utilize the water for domestic purposes. The structures in these small places are strung out along the major stream channel; they parallel the slope of the land along the axis of the alluvial fan.

Interestingly, *qanats* also underlie the street patterns of larger cities as well. In some cities, *qanat* water flows in tunnels beneath residential areas and surfaces near the cultivated area. Staircases from the surface (*payab*) reach down to these streams. The first *payab* usually is at a public cistern where drinking water is available to the entire community. Sometimes these cisterns are sizable vaults as much as l0 meters across and 15 or more meters deep with spiral stairs leading down to small platforms at water level. In cities like Herat in Afghanistan, these cisterns are ancient constructions encased in tile. Other more modest urban *payabs* are found along major streets, and even in some alleys, a factor that probably played an important role in the social and physical layout of the town.

Where tunnels run beneath houses, private *payabs* slope down to the stream providing water for various domestic uses. In wealthy homes, special rooms are constructed beside the underground stream with tall shafts reaching upward to windcatchers (*badgir*) above roof level. Air caught by the *badgirs* , which are oriented to prevailing summer winds, is forced down the shaft, circulates at water level, and provides a cool refuge from the afternoon heat of summer. Needless to say, land located above submerged *qanat* tunnels, and houses with private *payabs* , are highly valued (Honari l989).

Bonine has discerned an orthogonal street pattern in cities like Kirman, Yazd, and Sabzevar where long, straight streets intersect at right angles forming huge "superblocks" with many short, blind alleys branching off major thoroughfares at right angles (Bonine l979). These grids do not conform to the rigid geometry of classical Greek or Roman towns, but they have distinctly geometric configurations. In Bonine's view, these configurations were established on a network of water channels used to irrigate nearby orchards and fields. As in alluvial fan settlements, slope is crucial. Topography and water flow are the elemental principles of Iranian settlement geography (Bonine 1979).

SOCIAL PATTERNING

In some rural settlements, the location of structures reflects the dynamics of water use and social status. Above the village, particularly where the slope is relatively steep, one or more water mills (*asiab*) are built to grind the grain of nearby villages and hamlets. In these Norse-style mills, water drops five or more meters to power a vertical shaft that turns a heavy mill stone (Wulff 1966). Closer to the top of the settlement, at least one branch of the *qanat's* water is diverted at a *maqsam* to a public reservoir or cistern, a communal bath (*hammam*), and a mosque. The reservoir or cistern provides clean water to all people in the community. The communal baths, which are only found in larger settlements, are used by surrounding villagers for bathing. The pool of water at the mosque is used for religious ablutions in *kur*, or sacred water (English 1966).

Within the settlement, the location of each household compound along the primary stream determines the quantity and quality of its water supply. As a result, household location frequently reflects the social and economic status of its residents or owner. The more prosperous households of landlords, merchants, and religious leaders are in the upper section of the village where water is clean and plentiful. The courtyards of these dwellings display central pools with canals lined by flowers dividing the gardens into sections. The poorer households of small landowners, sharecroppers, and day laborers are located downstream in the village where the volume of water is diminished and more polluted. The compounds in this district are given over to the cultivation of alfalfa (for fodder), fruit trees, spices, herbs, and vines.

Qanats *usually are built by wealthy individuals, but the constant need for tunnel repairs owing to natural disasters or social dislocations leads to rapid fragmentation in ownership. Many* qanats *have as many as two to three hundred owners and the water of some* qanats *is divided into as many as 10,000 time shares.*

Moving downstream through the village, water loss by evaporation, seepage, and domestic use can result in as much as a 40% decrease in water available to the lower sections of the village. Though there is a difference in the price of a share of water depending on where it is used in the settlement, the price difference is rarely commensurate with water loss which varies considerably during the year. In most settlements, then, the powerful live in the upper reaches. The *qanat*, more often than not, enters the village at the household compound of the most influential local landlord (*arbab*) (Cressey 1959).

In larger towns watered by several *qanats*, these water-based social gadients often are obscured by settlement history. Frequently, a maze of twisting distributary channels covers the landscape whose diversions are vestiges of past business transactions, marriage agreements, and bequests. But in most settlements, social patterns are directly related to water quantity and quality. Alterations in one system involve changes in the other.

Variations in water quality from one part of a village to another are reduced by customs of sequential water use that demand cooperation, an example of community needs taking precedence over personal influence. As noted above, a public cistern is often located at the top of the settlement. Its water is reserved specifically for drinking and cooking. In a pool below the cistern, dishes and cutlery may be washed using sand as the cleansing agent. After water is directed to the communal bath, additional pools are drawn off from the main channel (*shahjub*) in which household utensils may be washed with soap, and still further downstream animals are watered and straw soaked for use in construction. After these communal needs are met, the now polluted water flows directly to the fields. This hierarchy of use conserves water and reduces pollution (Roaf 1989).

QANAT OWNERSHIP

Strict and unforgiving adherence to communal methods of water rotation and maintenance of the water supply system are perhaps most important in maintaining the social cohesion of qanat-*watered villages.*

In many villages, *qanat* ownership is widely diffused throughout the population, and this widespread stake in the water supply system reinforces social cooperation. *Qanats* usually are built by wealthy individuals, but the constant need for tunnel repairs owing to natural disasters or social dislocations leads to rapid fragmentation in ownership. Many *qanats* have as many as two to three hundred owners and the water of some *qanats* is divided into as many as 10,000 time shares.

In some cases, the system of dividing water goes back hundreds of years. The current division of water at Ardistan in central Iran, for example, dates back to the 1200s when Hulagu Khan, the grandson of Genghis Khan, ordered that the town's water be divided into twenty-one shares with each share allotted to a specific quarter (Lambton 1953).

A complete record of changes in ownership exists for the Vakilabad *qanat* built in Mahan, a town southeast of Kirman, in the 1860s (English 1989). Initially, its water was divided among three men in six shares. One-sixth of the water was allotted to the then custodian of the Shah Ni'matullah Vali Shrine. This portion has increased to one-third of the water and is now owned by twenty of his descendants. The remaining water was sold off bit by bit such that some seventy families now own shares in the *qanat*. In another *qanat* system in the same town, water ownership has fragmented to such a degree that the owner of the smallest portion has rights to only thirty seconds of water once every twelve days. In Lambton's view, the historic inability of the Iranian upper class to retain property intact over time is the primary reason that Iran never developed a feudal aristocracy comparable to that of medieval Europe (Lambton 1969).

WATER DISTRIBUTION AND SYSTEM MAINTENANCE

Strict and unforgiving adherence to communal methods of water rotation and maintenance of the water supply system are perhaps most important in maintaining the social cohesion of *qanat*-watered villages. The distribution of water in these settlements is based on ownership of time shares in the annual flow of a *qanat*. These rotations take account of variations in diurnal and seasonal flow as well as differences in plot location, soil conditions, rates of seepage, and evaporation.

In general, water is divided into an indefinite number of time shares, or *sahms*, in a given water rotation period (Lambton 1953; Bonine 1982). The *sahms* are measured by volume in terms of *qasabs*, the theoretical amount of water required to flood-irrigate an area of roughly thirty square yards once every twenty-four hours. One hundred *qasabs* (in theory) would irrigate an acre of land, except that a *qasab* varies in volume from one place to another. Moreover, *qanats* as well as subdivisions of *qanats* (e.g. streams created after division at a *maqsam*) rotate water on different time schedules ranging from once every six days or twelve days to once every eighteen, nineteen, twenty-one or twenty-two days. The length of the rotation period varies with volume of flow and crops under cultivation, but a host of other lesser environmental factors also come into play.

When communal efforts fail, village water supplies diminish and in some cases the settlements are abandoned. Government land reform programs in the 1960s, for example, required written deeds to determine water ownership. Some settlements honestly or otherwise produced deeds that taken together made up more than twenty-fours hours of water a day. The resulting chaos led to violent ownership disputes and sometimes to total social breakdown.

In a relatively simple example from Mahan near Kirman, water from one of the towns' four *qanats* is divided into fifteen *sahms* with a volume of forty *qasabs* per day on a twelve day rotation. In this case, each *sahm* is equal to ninety-six minutes of water once every twelve days or enough water to irrigate forty *qasabs* of land. In addition, each *sahm* is subdivided into six *dangs*, each composed of six *habbeh*. According to this measurement system, one *dang* would equal sixteen minutes of water and one *habbeh* a single minute of water once every twelve days.

Most systems of water distribution, however, are much more complex. In a more typical case based on another *qanat* in the same settlement, the flow of water passes through twelve separate water dividers or *maqsams* that allocate water to specific fields at specific times on specified days in a conjoined eighteen, nineteen, and twenty-one day rotation (English 1989).

The person responsible for guiding the water through channels to the right field at the right time is the water master (*mirab*) or water bailiff (*mubashiri ab*). This official often directs a bevy of assistants who keep the channels clean, open and close small gates to specific fields, and breach levees when required. In some smaller communities, these tasks are handled directly by the community of water users (Spooner 1974). In the past, *mirabs* measured units of flow with a water clock (*tas*) based on the time it took for a metal cup with a hole in the bottom to sink in a container of water. Recently, these clepsydras have been replaced by clocks.

Annual repairs and cleaning of the *qanat* are usually required to maintain its flow, and communal meetings of *qanat* owners are held to decide the annual allocation of funds for this purpose. Although large water owners tend to dominate these meetings, votes are cast by shares. Other system responsibilities such as the payment of the *mirab*, his assistants, and crop watchers (either in cash or kind) are also decided in this fashion. In addition, more general community needs are dealt with by vote or custom—among these are payments to the carpenter, blacksmith, and other artisans vital to village life. Although social equality is rare in *qanat*-watered villages, village cooperation is a necessary adaptation to the ecological and social demands of this water technology. This social cohesion, and the water systems they are designed to preserve, defined the lifeworlds of Iranian villagers.

When communal efforts fail, village water supplies diminish and in some cases the settlements are abandoned. Government land reform programs in the 1960s, for example, required written deeds to determine water ownership. Some settlements honestly or otherwise produced deeds that taken together made up more than twenty-fours hours of water a day. The resulting chaos led to violent ownership disputes and sometimes to total social breakdown. In other very small settlements where disputes over water rights occurred, lotteries were held on the autumnal equinox in an effort to distribute scarcity more equitably. Water owners formed a circle, and at a signal from the village headman threw out any number of fingers on one or two hands. Starting with the headman, the fingers were counted around the circle of owners. Counting off the resultant total, the person at the end of the count received water on the first hour of the first day of the rotation. The lottery continued until each man had a definite time to receive water. Needless to say, owners near the end of the rotation usually received no water.

CONCLUSION

Qanats are renewable water supply systems that have sustained agricultural settlement on the Iranian plateau for millennia. By their very nature, *qanats* have encouraged sustainable water use. Their major limitations are that they are expensive to build and produce relatively small amounts of water. As a result, few *qanats* are being built today. Instead, *qanats* are being replaced by deep wells which produce more water to meet the current demand and support more intensive patterns of land use.

These deep wells mine water from fossil aquifers at rates well beyond replacement levels. Most are drilled in basin areas where water tables are close to the surface. As aquifers are drained, the *qanats* of alluvial fan settlements that share the same aquifer dry up when the water table lowers, and settlements eventually disappear. The communal patterns of social adaptation that bound together the lifeworlds of Iranian villagers for centuries disappear as well. In fact, evidence suggests that deep wells have made many small farmers dependent on well owners, have failed to increase agricultural production significantly, and bode poorly for the long term survival of many long-established settlements (Ehlers and Saidi 1989; Kielstra 1989). The desire for short term benefits has prevailed; the long term costs remain to be seen.

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