THE ORIGIN AND SPREAD OF QANATS IN THE OLD WORLD

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INTRODUCTION

Subterranean tunnel-wells (*qanats*) are extremely important in the history of irrigation and human settlement in the arid lands of the Old World.[1] Apparently originating in pre-Achaemenid Persia, tunnel-wells spread to Egypt, the Levant, and Arabia in Achaemenid times (550–331 B.C.). The Arabs carried *qanats* across North Africa into Spain and Cyprus; they are also found in Central Asia, western China, and on a more limited scale in dry regions of Latin America. In modern times, more than twenty terms are used to identify these horizontal wells; the Arabic word *qanāt* meaning "lance" or "conduit" is used in Iran, the Persian term *kārīz* is used in Afghanistan, while in Syria, Palestine, and North Africa *fuqarā* (pronounced foggara) is the most common term. In all of these regions, tunnel-wells are still being constructed in the traditional manner, and many settlements depend on them for irrigation and domestic water. Where used, *qanats* have strongly influenced village socio-economic organization and patterns of ownership and tenure.

THE NATURE OF QANATS

Qanats are gently sloping tunnels dug nearly horizontally into an alluvial fan until the water table is pierced. Once constructed, ground water filters into the channel, runs down its gentle slope, and emerges at the surface as a stream (fig. 1). In excavating these tunnels, diggers must have air and tunnel spoil must be removed, so the tunnels are connected to the surface with a series of vertical shafts spaced every 50 to 150 meters along its course. The tops of these shafts are rimmed by piles of excavated dirt to form a "chain-of-wells" on the surface, a distinctive feature of the arid landscapes of *qanat*-watered regions (figs. 2, 3). This system of water supply is widely used in the deserts of the Old World for several reasons. First, unlike other traditional irrigation devices such as the counterpoised sweep (*shaduf*), the Persian wheel (*dulab*), and the noria (*na'urah*), *qanats* require no power source other than gravity to maintain flow.[2] Second, water can be moved substantial distances in these subterranean conduits with minimal evaporation losses and little danger of pollution. Finally, the flow of water in *qanats* is proportionate to the available supply in the aquifer, and, if properly maintained, these infiltration channels provide a dependable supply of water for centuries.

Qanats vary considerably in size. Those in mountainous areas are usually short, shallow tunnels only tens of meters long and several deep, which draw surface water from small patches of alluvium. Others are major engineering feats such as those which supply water to the Iranian cities of Kirman, Yazd, and Birjand. At Kirman, *qanats* extend more than 50 kilometers southward to penetrate the water table at the base of the Kuhi Jupar (fig. 4).[3] Literally thousands of vertical shafts, the deepest 100 to 125 meters, dot the Kirman Plain marking the courses of an unknown number of galleries which carry water to the city (fig. 2). Yazd is watered by some 70 *qanats*, 30 to 45 kilometers in length, with mother wells (that shaft furthest from the point where water emerges

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[1] Field work for this study was supported by the Foreign Field Research Program of the National Academy of Sciences—National Research Council. Michael E. Bonine drew figures 1 and 4.

General articles on tunnel-wells include: George B. Cressey, "Qanats, Karez, and Foggaras," *"Geographical Review* **48** (1958): pp. 27–44; Carl Troll, "Qanat-Bewässerung in der Alten und Neuen Welt," *Mitteilungen der Österreichischen Geographischen Gesellschaft* **105** (1963): pp. 313–330; Johannes Humlum, "Underjordiske Vandingskanaler: Kareze, Qanat, Foggara," *Kultergeografi* **16** (1965): pp. 81–132; Hans E. Wulff, *The Traditional Crafts of Persia* (Cambridge and London, 1966), pp. 249–256; "The Qanats of Iran," *Scientific American* **218** (1968): pp. 94–105.

[2] Jørgen Laessøe, "Reflexions on Modern and Ancient Oriental Water Works," *Journal of Cuneiform Studies* **7** (1953): pp. 5–26; Charles Singer, ed., *A History of Technology* (5 v., Oxford, 1954) **1**: pp. 531–535; A Molenaar, *Water Lifting Devices for Irrigation,* FAO Agricultural Development Paper **60** (Rome, 1956).

[3] Philip H. T. Beckett, "Qanats around Kirman," *Journal of the Royal Central Asian Society* **40** (1953): pp. 47–58; Paul Ward English, *City and Village in Iran* (Madison, 1966), pp. 135–140.

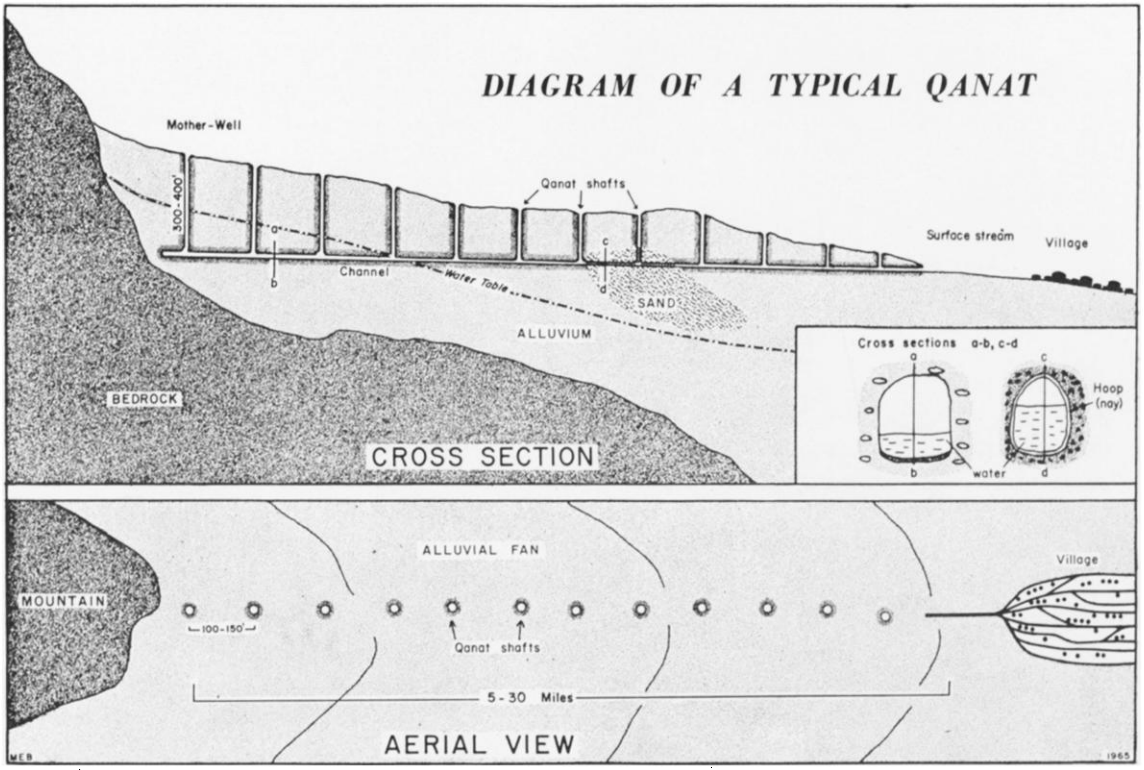

FIG. 1. Diagram of a typical *qanat*. Profile, cross sections, and aerial view illustrating the varying dimensions of a tunnel-well.

at the surface) 50 to 125 meters deep.[4] The deepest reported *qanat* is located at the village of Gunabad near Birjand.[5] Though only 27 kilometers long, its mother well lies at a depth of more than 300 meters.

QANAT CONSTRUCTION

Most *qanats* in Iran are constructed by a class of professional diggers (*muqannis*) who inherited this task from the slaves and captives of the Achaemenid and Sassanian kings. These men form a community of traveling artisans, migrating from place to place as floods destroy *qanats* in one area or a lowered water table demands that *qanat* tunnels be lengthened in another. The tools of the *muqanni* are primitive: a broad-bladed pick, a shovel, and a small oil lamp. His profession is well paid but hazardous. The *muqanni* must work with water flowing around him, ventilation is poor, and the chances of cave-ins are great. Today, *qanats* are still being built by these *muqannis* and the techniques of construction have changed little.

Site selection is the first step in the construction of a *qanat*. Local slope conditions, ground-water supplies, and the proposed location of the new settlement determine this decision. These factors are weighed by an expert, usually one of the older, more famous *muqannis*, who decides where a trial well should be dug. Favorable sites often lie near the mouth of a wadi, but where the water table is deep and the *qanat* long, the general topographic setting and variations in vegetation are used as indexes of the likely location of underground water supplies.

After the expert has chosen the site, a vertical shaft deep enough to penetrate the permanent water table is dug. The *muqanni* must be certain that this well has penetrated the permanent water table or has struck a constant flow of ground water on an impermeable stratum. If there is doubt concerning the water supply's permanence, more test holes are dug to determine the extent of the aquifer and the depth of the water table. When a trial well has sufficient water, it becomes the starting

[4] British Admiralty, *Persia,* Geographical Handbook Series **BR525** (London, 1945), p. 541.

[5] E. Noel, "Qanats," *Journal of the Royal Central Asian Society* **31** (1944): p. 192.

FIG. 2. Aerial photograph (1: 18,750) illustrating the "chain-of-wells" effect of *qanats* located south of the city of Kirman, Iran. Note *qanat* entering gardens in upper right.

point for the construction of a *qanat*. This shaft will be called the mother well (*madari chah*) of the *qanat*, though the term is misleading because water is not removed from the ground at this point. The length of the *qanat* is measured from the mother well to the point where water surfaces. The depth of the mother well may vary from ten to several hundred meters.

The *muqanni* next establishes the alignment and grade of the *qanat* and this is the most difficult

FIG. 3. Detailed aerial photograph (1:3,000) of *qanats* at the southern margin of the city of Kirman, Iran. Note their passage through abandoned fields in the lower center.

engineering task in the entire operation.[6] The *qanat* is aligned so that a gently sloping tunnel from the water-filled base of the mother well will surface *above* the irrigated fields of the settlement. If the tunnel emerges far from the settlement, water will flow on the surface in an open channel to the houses and fields. In such cases, evaporation and seepage become major problems, as at Turbat-i Haidari in eastern Iran where only one-quarter of the *qanat* water actually reaches the fields.[7] If the gradient of the tunnel is too steep, water rushing down the tunnel will erode the walls and soon destroy it. The maximum gradient in a short *qanat* is approximately 1:1,000 or 1:1,500; in a long *qanat* the tunnel is nearly horizontal. Using a string as a level, a skilled *muqanni* can

[6] This process was not observed in the field. It is described in: *ibid.*, pp. 196–197; Philip H. T. Beckett, *op. cit.* **40** (1953): pp. 48–49; Hans E. Wulff, *op. cit.* (1966), pp. 252–253.

[7] F. H. Kochs K. G., *Rural Development Plan, South Khorassan: Preliminary Study* (Tehran, 1959), p. 29.

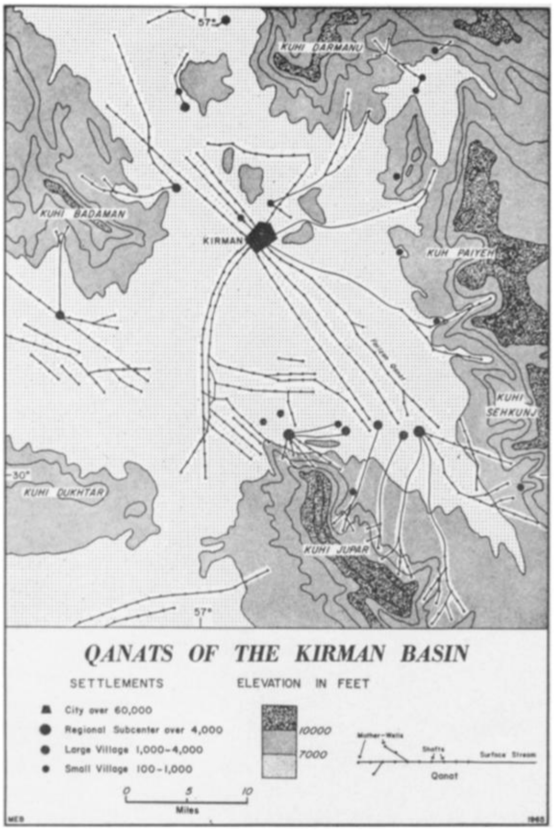

FIG. 4. *Qanats* of the Kirman Basin. The radial pattern of tunnel-wells around the city of Kirman, Iran, is repeated in many cities of the Old World.

establish such a grade, even when the tunnel passes beneath several kilometers of rough terrain.

Actual construction of the tunnel begins after the alignment and grade of the *qanat* have been determined. Work starts in the dry section of the *qanat* at the downslope end. The tunnel is dug back toward the mother well, with vertical shafts connecting the tunnel to the surface every 50 to 100 meters. In some cases, the vertical shafts are dug first and the tunnel is constructed to connect the bottoms of the shafts.

A team headed by a *muqanni* collaborates in the construction of a *qanat*. With a small pick and shovel, he excavates a tunnel roughly a meter wide and 1.5 meters high. An apprentice packs the dirt into a rubber bucket, and two laborers at the surface haul the dirt up the shaft by turning a windlass. If the *qanat* tunnel lies at a depth of more than 100 meters, a second windlass is set in a niche half way down the vertical shaft and the dirt is transferred from one bucket to another at this point.

The major problems in constructing a *qanat* occur when the tunnel enters the water-bearing section, where many *muqannis* are drowned or suffocated each year. In some cases the shafts fill with water before having reached the proper depth and the *muqanni* must dig upward beneath this pool and avoid the rush of water when a breakthrough is made. If the tunnel passes through an area of soft sand, clay hoops are inserted in the tunnel to prevent collapse (fig. 1). Where ventilation is poor, extra vertical shafts are dug to prevent suffocation. Every *muqanni* carries a castor oil lamp; when the air no longer keeps its flame lit, he leaves the tunnel and another shaft is built. In Yazd, where the *qanats* are very deep, vertical shafts are built on either side of the tunnel. A lamp is placed at the bottom of one shaft to create an updraft which draws air down the other shaft and improves ventilation.[8] Sometimes twin *qanats* are built side-by-side, enabling the *muqanni* to move from one to the other.

The time required to build a *qanat* varies with the capital of the owner, underground soil and water conditions, the amount of water desired, and the skill of the *muqanni*. Two new *qanats* recently built at the villages of Javadieh and Hujatabad south of Kirman can be used as examples. The Hujatabad *qanat* is only one kilometer long, with a mother well 45 meters deep, but it was under construction for twenty-seven years because of three changes in ownership. Construction on the Javadieh *qanat* began in 1941 and one team of *qanat*-diggers worked daily for seventeen years to bring water to the surface. In 1958, when small amounts of water began to flow, the owner hired a second team to work at night. Now the Javadieh *qanat* is 3 kilometers long; its tunnel bifurcates and has two mother wells at 50 and 55 meters respectively. Most of the tunnel had to be lined with clay hoops because of loose sand. It cost $33,000 to build this *qanat* and it now irrigates about one-half acre of land every twenty-four hours.

On this basis, *qanats* cost about $10,000 per kilometer to build. The Javadieh *qanat* cost more, $11,000 per kilometer, because the tunnel was lined. The expense of this relatively short *qanat* indicates the monumental costs of constructing a new long *qanat*. Such a one to Kirman, 40

[8] The diagram illustrating this device in E. Noel, *op. cit.* 31 (1944): p. 198 has been printed upside down.

kilometers long with a mother well 90 meters deep, cost approximately $213,000 when completed in 1950. Because of inflation and higher wages, the capital costs of constructing this *qanat* today would be about $387,000.

THE DISTRIBUTION AND DIFFUSION OF QANATS

Qanat technology apparently originated in the highlands of western Iran, northern Iraq, and eastern Turkey some 2,500 years ago, possibly in connection with early mining ventures in that region.[9] Laessøe has argued that *qanats* supported a flourishing civilization near Lake Reza'iyeh (Urmia) which was destroyed by Sargon II in his eighth campaign in 714 B.C., but unfortunately this information is based on a badly damaged tablet.[10] It is certain, however, that later Assyrian cities, particularly those on the Tigris River, relied on *qanats* for their drinking water. One *qanat* built during this period bears the inscription of Sargon's successor, Sennacherib (705–681 B.C.); this conduit, some 20 kilometers long with shafts spaced every 45 meters, still carries water to the city of Arbil.[11] The capital city of the Medes, Ecbatana (modern Hamadan), was also watered by *qanats* in the seventh century B.C.[12] and Darius' capital at Istakhr may also have used this water supply system.[13]

The core area of *qanats* then lies in the realm of the Persians whose language is rich in words relating to *qanat* technology and where *qanats* are very old, very numerous, and construction techniques are fully developed. *Qanat* technology was widely applied on the Iranian Plateau by Parthian times [14] on the numerous piedmont alluvial plains, where near horizontal tunnels can intersect sloping water tables, which provide an ideal setting for *qanat* construction. In modern times, most of the major cities in Iran including Tabriz, Qazvin, Saveh, Tehran, Yazd, and Kirman rely on *qanats* for domestic and irrigation water and chains of wells radiate outward from each of them (fig. 4). It is estimated that nearly 15 million acres of cultivated land, one-third to one-half of the irrigated area of Iran, are watered by some 37,500 *qanats* of which an estimated 21,000 are in fully operating order and 16,500 are used but need repair.[15] Their aggregate length has been placed at more than 160,000 kilometers; their total discharge at 20,000 cubic meters per second.[16] The Nishapur Plain near Mashhad alone is reputed to have "12,000 springs fed by 12,000 *qanats*." [17] Though these figures are suspect, having never been verified by field work, there is no doubt that *qanats* are the major source of irrigation water in Iran.

The first diffusion of *qanats* out of this core area occurred in the Achaemenid period when the Persians established an empire extending from the Indus to the Nile. To the west, the Persians car-

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[9] A supposition based on (1) the early evidence for *qanats* in this region, (2) the fact that *qanats* differ little from the horizontally driven adits of early miners, and (3) Armenia's reputation as one of the oldest mining and metallurgical centers in the Middle East.

[10] Jørgen Laessøe, "The Irrigation System at Ulhu, 8th Century B.C.," *Journal of Cuneiform Studies* **5** (1951): pp. 21–32; R. J. Forbes, *Studies in Ancient Technology* (6 v., Leiden, 1955–1958) **1**: p. 153 *ff*. The precise location of this irrigation system has been identified as modern Ula (Ulagh) at the northwest end of Lake Reza'iyeh by Edwin M. Wright, "The Eighth Campaign of Sargon II of Assyria (714 B.C.)," *Journal of Near Eastern Studies* **2** (1943): pp. 173–186.

[11] W. A. MacFadyen, "The Early History of Water-Supply: Discussion," *Geographical Journal* **99** (1942): pp. 195–196; Charles Singer, ed., *op. cit.* **1** (1954): pp. 533–534; R. J. Forbes, *op. cit.* **2** (1955–1958): pp. 21–22.

[12] Henri Goblot, "Dans l'ancien Iran, les techniques de l'eau et la grande histoire," *Annales: économies-sociétés-civilisations* **18** (1963): p. 510.

[13] E. Merlicek, "Aus Irans Kulturvergangenheit: Wasserwirtschaft und Kultur in ihren Zusammenhängen und gegenseitigen Beziehungen," *Deutsch Wasserwirtschaft* **36** (1941): pp. 301 *ff*.; Carl Troll, *op. cit.* **105** (1963): p. 314.

[14] An important passage from Polybius (*Historiae*, X. 28) states that *qanats* were widespread in Persian territory early in Parthian times (248 B.C.–A.D. 224). Stein's archaeological evidence supports this statement. Aurel Stein, "Archaeological Reconnaissances in Southern Persia," *Geographical Journal* **83** (1934): pp. 122–124, 132. Other early writers who discuss *qanats* include the Greek geographer Megasthenes [quoted in R. J. Forbes, *op. cit.* **1** (1955–1958): p. 153] and the Roman architect and engineer Pollio Vitruvius (*De Architectura*, VIII. 6.3.)

[15] Farhad Ghahraman, *The Right of Use and Economics of Irrigation Water in Iran* (Ann Arbor, 1958), pp. 44–45; Henri Goblot, "Le Problème de l'eau en Iran," *Orient* **23** (1962): p. 50. Other discussions of *qanats* in Iran include: B. Fisher, "Irrigation Systems of Persia," *Geographical Review* **18** (1928): pp. 302–306; Fritz Hartung, "Wasserwirtschaft in Iran," *Der Kulturtechniker* **39** (1935): pp. 78–85, 175–192; Gholam-Resa Kuros. *Irans Kampf um Wasser* (Berlin, 1943); Hans E. Wulff, *op. cit.* **218** (1968): pp. 94–105.

[16] This figure was originally suggested by E. Noel, *op. cit.* **31** (1944): p. 191 and is repeated in George B. Cressey, *op. cit.* **48** (1958): p. 39 and R. N. Gupta, *Iran: An Economic Survey* (New Delhi, 1947), p. 46.

[17] Clifford E. Bosworth, *The Ghaznavids: Their Empire in Afghanistan and Eastern Iran, A.D. 944–1040* (Edinburgh, 1963), pp. 155–157; George B. Cressey, *op. cit.* **48** (1958): p. 38.

ried *qanat* technology across the Fertile Crescent to the shores of the Mediterranean and southward to Egypt and Saudi Arabia. In the Iraqi foothills of the Zagros, *qanats* water the cities of Kirkuk and Arbil.[18] Deeper in the foothills, the city of Sulaymaniyah receives its entire water supply from tunnel-wells.[19] In Palestine and Syria, *qanats* are found in the Jordan Valley, in the Qalamun region of eastern Syria, near Palmyra, and northeast of Aleppo.[20] Recently, several *qanats* have been uncovered in the Wadi Arava south of the Dead Sea at the oases of Ein Dafieh, Yotvata, and Ein Zureib; the Ein Dafieh *qanats* empty into a reservoir used in Persian and later Roman times.[21] In Syria accurate dating is a problem because some *qanats* are ancient, others were constructed in the Byzantine period, and a few are recently built. At the village of Michrife-Qatna, which occupies the site of an old Hittite fortress 18 kilometers northeast of Homs, a *qanat*-like canal apparently supplied water to the town very early.[22] The more elaborate Byzantine *qanat* systems at Moufaggar, Amsareddi, and Qadeym (ancient Acadama) are Roman or repaired Persian constructions.[23] *Qanats* on the Selemiya Plain, however, have been built and renovated by the Ismailis who settled this region in the 1870's.[24]

In Egypt *qanats* built during the Persian occupation (525–332 B.C.) are found in the Kharga Oasis and at Matruh.[25] Beadnell measured one of these tunnel-wells, which at Kharga are dug into soft sandstones, and found 150 shafts on a line 3,200 meters long; he estimated that 4,875 cubic meters (about 11,000 tons) of rock had been removed from that tunnel and its shafts alone.[26] Agricultural colonies in the early 1900's cleared some of the ancient Kharga *qanats*, which had been choked with debris for more than a millennium, and they still supplement surface water supplies today.[27] At Matruh *qanats* were driven beneath consolidated sand dunes into limestone and were closed with cement caps.[28] *Qanat* construction in solid rock is rare elsewhere in the Old World.

The Persians also introduced *qanats* into Arabia in the fifth century B.C. and they are still used in the Hijaz, in the mountains of Yemen, along the Hadhramaut, in Oman, and at the Al Kharj oasis southeast of Riyadh and the Al Qatif oasis north of Dhahran.[29] Underground conduits are found in the Wadi Fatima west of Mecca and similar channels carry water to this holy city from Ain Zobeida to the southeast. *Qanats* also carry water to several quarters in Medina from a spring at Ain Zarqa south of the city.[30] The mountains west of San'a have *qanats* as do some districts in the central highlands of Najd. *Qanats* are most numerous in Oman where they are called *aflaj*; in Yemen and the Hadhramaut they are called *felledj*. At Al Kharj the *qanats* are specifically attributed to

18 C. E. N. Bromehead, "The Early History of Water-Supply," *Geographical Journal* **99** (1942): pp. 195–196. See also: F. Krenkow, "The Construction of Subterranean Water Supplies during the Abbaside Caliphate," *Transactions of the Glasgow University Oriental Society* **13** (1951): pp. 23–32.

19 W. A. MacFadyen, *Water Supplies in Iraq*, Iraq Geological Publications **1** (Baghdad, 1938).

20 Nelson Glueck, "Some Ancient Towns in the Plains of Moab," *Bulletin of the American Schools of Oriental Research* **91** (1943): pp. 9–10; B. Aisenstein, "The 'Kahrez', an Ancient System of Artificial Springs," *Journal of the Association of Engineers and Architects in Palestine* **8** (1947): pp. 2–3; A. Reifenberg, *The Struggle between the Desert and the Sown* (Jerusalem, 1955), pp. 53–54.

21 M. Evanari, L. Shanan, N. H. Tadmor, and Y. Aharoni, "Ancient Agriculture in the Negev," *Science* **133** (1961): pp. 979–997.

22 Mesnil du Buisson, *La Site archéologique de Michrife-Qatna* (Paris, 1935), p. 53, pl. XI.

23 A. Poidebard, *La Trace de Rome dans le désert de Syrie.—Le limes de Trajan à la conquête arabe.—Recherches aériennes (1925–1932)*, Bibliothèque archéologique et historique **18** (Paris, 1934); R. Mouterde and A. Poidebard, *Le Limes de Chalcis*, Bibliothèque archéologique et historique **38** (2 v., Paris, 1945) **2**: plans 2–4.

24 Norman N. Lewis, "Malaria, Irrigation, and Soil Erosion in Central Syria," *Geographical Review* **39** (1949): p. 286.

25 A. T. Olmstead, *History of the Persian Empire* (Phoenix ed., Chicago, 1948), p. 224.

26 H. J. L. Beadnell, *An Egyptian Oasis: An Account of the Oasis of Kharga in the Libyan Desert, with special reference to its History, Physical Geography, and Water-Supply* (London, 1909), p. 171; "Remarks on the Prehistoric Geography and Underground Waters of Kharga Oasis," *Geographical Journal* **81** (1933): pp. 128–139.

27 G. W. Murray, "Water from the Desert: Some Ancient Egyptian Achievements," *Geographical Journal* **121** (1955): pp. 171–181.

28 G. F. Walpole, *An Ancient Subterranean Aqueduct West of Matruh*, Survey of Egypt **42** (Cairo, 1932).

29 George B. Cressey, *op. cit.*, **48** (1958): pp. 42–43; Carl Troll, *op. cit.* **105** (1963): p. 318; Johannes Humlum, *op. cit.* **16** (1965): p. 102.

30 British Admiralty, *Western Arabia and the Red Sea*, Geographical Handbook Series **BR 527** (London, 1946), pp. 33–34.

Persian workmanship, as the name of a nearby ridge, Firzan, attests.[31]

East of Iran, *qanats* are used in Afghanistan, Central Asia, and Chinese Turkestan (Sinkiang). Here, *qanats* are called by their Persian term (*kariz*) rather than the Arabic *qanat*, yet whether this technology spread eastward during the Achaemenid diffusion or at some later period is uncertain. In Afghanistan *qanats* are a major source of irrigation water in the south and southeast, especially around the city of Qandahar.[32] In Pakistani Baluchistan, approximately two-thirds of the water in the city of Quetta is supplied by *qanats*, which also irrigate some 90,000 acres of land in the vicinity.[33] *Qanats* were apparently used in western China as early as the second century B.C., yet Huntington claims that they were not used in the Turfan Basin, which has one of the most extensive *qanat* systems in the world, until the eighteenth century.[34] In modern times approximately 40 per cent of the people in this region depend for water on *qanats* dug by imported Turki laborers.[35]

In a second major diffusion, *qanat* technology spread with Islam and the Arabs across North Africa into Spain, Cyprus, and the Canary Islands in the seventh and eighth centuries A.D. In North Africa *qanats* (here called *fuqarā*) are widely distributed, though having been built and maintained by Negro slave specialists, new constructions are rare.[36] In Libya they are found in the Kufra oases and in the Fezzan, particularly at Ghadames.[37] In Tunisia *qanats* have been reported north of the Chott Djerid [38] and in Algeria, on the borders of the Tademait Plateau in the Touat and Tidikelt districts south of the Great Western Erg.[39] In Morocco *qanats* are called *khettara* or *rhettara* and are used on the northern slopes of the Atlas, particularly around the city of Marrakech,[40] and south of the Atlas in the Tafilalt.[41] It is in these last three regions, in the Tademait district of southern Algeria, near Marrakech, and in the Tafilalt of Morocco, that *qanats* reach their greatest development outside the Persian core area.

Qanats were introduced into the Touat and Tidikelt districts of Algeria several centuries before the Arab conquest by Jews or Judaized Berbers fleeing from Cyrenaica during Trajan's persecution in A.D. 118.[42] These refugees were the first Jewish colonists in the Tademait region, establishing their capital at Tamentit south of Adrar.[43] Having absorbed the fundamentals of *qanat* technology during their long stay in Persian territory, first in Palestine and later in Cyrenaica, these Jews introduced *qanats* into the Western Sahara. In this region today, more than 1,500 kilometers of *qanat* tunnels can be found.[44] Near Aoulef al

31 D. G. Hogarth, "Some Recent Arabian Explorations," *Geographical Review* **11** (1921): p. 336; Douglas D. Crary, "Recent Agricultural Developments in Saudi Arabia," *Geographical Review* **41** (1951): p. 368. The importance of *qanat* irrigation to the existence of settlement in this region is a dramatic theme in the novel by Hammond Innes, *The Doomed Oasis* (New York, 1960).

32 Johannes Humlum, "L'Agriculture par irrigation en Afghanistan," *Comptes rendus, Congrès International de Géographie, Lisbon, 1949,* **3** (1951): pp. 318–328.

33 C. W. Carlston, "Irrigation Practices in the Quetta-Pishin District of Baluchistan, Pakistan," *Annals of the Association of American Geographers* **43** (1953): p. 160.

34 Huntington's evidence, which was based on local interviews, is given negative support by the lack of any references in Chinese sources to *qanats* in the Turfan Basin down to T'ang times and even later. Ellsworth Huntington, *The Pulse of Asia* (New York, 1907), pp. 310, 317; Aurel Stein, "Note on a Map of the Turfan Basin," *Geographical Journal* **82** (1933): pp. 236–246.

35 L. Wawrzyn Golab, "A Study of Irrigation in East Turkestan," *Anthropos* **46** (1951): pp. 187–199.

36 Though Pond has recently described the construction of a new *qanat* at Aoulef al Arab in southern Algeria. Alonzo W. Pond, *The Desert World* (New York, 1962), pp. 173–176.

37 James R. Jones, *Brief Resumé of Ground Water Conditions in Libya,* (Benghazi, 1960), p. 20; personal communication, March 16, 1964.

38 Marcel Solignac, "Recherches sur les installations hydrauliques de Kairouan et les steppes tunisiennes du VIIe au XIe siècle," *Annales de l'institut d'études orientales* **10** (1952): pp. 1–9; J. Despois, *La Tunisie, ses régions* (Paris, 1961), pp. 60–61.

39 Cne. Lô, "Les Foggaras du Tidikelt," *Travaux de l'institut des recherches sahariennes* **10** (1953): pp. 139–181; **11** (1954): pp. 49–79; Lt. Voinot, "Le Tidikelt: étude sur le géographie, l'histoire, et les mœurs du pays," *Bulletin de la société de géographie et d'archéologie d'Oran* **29** (1909): pp. 185–216, 311–366, 419–480.

40 Pierre Troussu, "Les Rétharas de Marrakech," *France-Maroc* **3** (1919): pp. 246–249; P. Fénélon, "*L'irrigation dans le Haouz de Marrakech,*" *Bulletin de l'association de géographes français* **18** (1941): pp. 63–70.

41 Jean Margat, "Les Recherches hydrogéologiques et l'exploitation des eaux souterraines au Tafilalt," *Mines et géologie* (Rabat) **4** (1958): pp. 43–68; "Les Ressources en eau des palmeraies du Tafilalt," *Bulletin économique et social du Maroc* **22** (1958): pp. 5–24.

42 Lloyd C. Briggs, *Tribes of the Sahara* (Cambridge, Mass., 1960), pp. 11–12.

43 Cressey estimates that there are now 40 kilometers of *qanat* tunnels in Tamentit with mother wells 60–75 meters deep. George B. Cressey, *op. cit.* **48** (1958): p. 44.

44 Estimates vary. Gerster, for example, states that there are about 3,000 kilometers of tunnels on the borders of the Tademait with a total yield of 600 gallons per second. Georg Gerster, *Sahara* (New York, 1961), p. 74.

Arab, forty *qanats* now produce about 7,000 gallons of water per minute to support some 8,000 people scattered over 31,000 square kilometers.[45] At the oasis of In Salah, the upkeep of existing *qanats* alone cost the administration more than 115,000 working days each year.[46]

Qanats were first built in Marrakech in the eleventh century A.D. during the reign of the Almoravides.[47] Today some 85 *qanat* systems are found on the Haouz plain, 40 of which are functioning and carry water to the city.[48] Most of these systems are rather short; the largest lie to the south of the city, are 4–5 kilometers long, and reach a maximum depth of 70 meters. In the Tafilalt, *qanats* are most numerous in the oases of Tadrha, Ferkla, Jorf, and Siffa south and west of Ksar es Souk. Margat found 273 *qanats* in this region, 145 in good condition, providing 1,100 liters of water per second to irrigate some 850 hectares of palm groves.[49]

Qanat technology spread into Europe with Arab culture; they were used marginally in the Spanish province of Catalonia and at Madrid [50] and are still a major source of water in Cyprus and the Canary Islands. Recently, abandoned *qanats* were discovered in Central Europe, in Bavaria and Bohemia, though when or how *qanats* spread into that region is unknown.[51] In Cyprus the total flow from all *qanats* amounted to 9.25 billion gallons in 1950 with an additional capacity of 1.85 billion gallons then under construction.[52] In the Canary Islands, Tenerife and Gran Canaria are literally dotted with *gálerias*, as *qanats* are called here and in Latin America.[53] Until recently, it was assumed that the New World *qanats* which are found in Mexico at Parrás, Canyon Huasteca, Tecamenchalco, and Tehuacán and in the Atacama regions of Peru and Chile at Nazca and Pica were introduced into the Americas by the Spaniards. It appears, however, that the *qanat* systems of the Atacama region may predate the Spanish entry into the New World; thus *qanats* have become an additional item in the continuing pre-Columbian trans-Pacific diffusion controversy.[54]

SOME SOCIO-ECONOMIC CONSIDERATIONS

Qanats are expensive to build and expensive to maintain, but their distribution in the dry lands of the Northern Hemisphere is nearly circumglobal, because for centuries *qanats* have been the most economic means of water supply in regions where water is the critical scarcity. Most *qanats* were built by powerful political rulers and in countries like Iran each leader was evaluated on the basis of the number of *qanats* (and mosques) constructed during his reign. The *qanat* was built of local materials; slaves were given the task of constructing them and maintenance was solved by a corvée. In recent times, however, deep wells which have several advantages over *qanats* have been introduced into *qanat*-watered regions. Deep wells are not limited by slope or soil conditions and can be placed at locations convenient in terms of transportation, market, or other considerations; they draw water from the permanent aquifer thereby eliminating seasonal variations in flow. Nor is water wasted when demand falls short of supply.[55] But altering or replacing the *qanat* system with deep wells requires major adjustments in social patterns, customs, and laws that have developed around this water-supply system; thus a conflict between these two technologies is developing.

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45 Lloyd C. Briggs, *op. cit.* (1960): p. 11. Production figures for individual *qanats* can be found in: André Cornet, "Essai sur l'hydrogéologie du Grand Erg Occidental et des régions limitrophes: les foggaras," *Travaux de l'institut des recherches sahariennes* **8** (1951): pp. 84–104.

46 Georg Gerster, *op. cit.* (1961), p. 76.

47 Pond states that the first *qanat* was built at Marrakech by Ubaid Allah ibn Yamus in 1078 A.D. Alonzo W. Pond, *op. cit.* (1962), pp. 175–176.

48 George S. Colin, "La Noria marocaine et les machines hydrauliques dans le monde arabe," *Hespéris* **14** (1932): pp. 38–39; Jeanne-Marie Poupart, "Les Problèmes de l'eau à Marrakech," *Les Cahiers d'Outre-Mer* **2** (1949): pp. 38–53.

49 Jean Margat, *op. cit., Mines et géologie* (Rabat) **4** (1958): p. 48.

50 J. Oliver Asín, *Historia del nombre Madrid* (Madrid, 1959), pl. XVII and map.

51 Helmut Klaubert, "Qanats in an Area of Bavaria—Bohemia," *Geographical Review* **57** (1967): pp. 203–212.

52 George B. Cressey, *op. cit.* **48** (1958): p. 42. For details see: C. Raeburn, *Water Supply in Cyprus* (2nd ed., Nicosia, 1945).

53 There were 305 *qanats* on Tenerife in 1960. See map in: Johannes Humlum, *op. cit.* **16** (1965): p. 107.

54 Karl Kaerger, *Landwirtschaft und Kolonisation im Spanischen Amerika* (2 v., Leipsig, 1901) **2**: pp. 251–254; J. Simon, "Oasenkultur in der chilenischen Wüste Atacama," *Tropenpflanzer* **11** (1907): pp. 387–392; H. Kinzl, "Die künstliche Bewässerung in Peru," *Zeitschrift für Erdkunde* **12** (1944): pp. 98–110; Carl Troll, *op. cit.* **105** (1963): pp. 321–329; Johannes Humlum, *op. cit.* **16** (1965): pp. 108–113.

55 A comparison of the economics of *qanats* versus deep wells can be found in: Overseas Consultants, *Report on the Seven Year Development Plan for the Plan Organization of the Imperial Government of Iran* (3 v., New York, 1949) **3**: pp. 149–151, 191–192.

After *qanats* came into widespread use in the Muslim World, a body of custom and law (*sharī'a*) developed to regulate the water-supply system. The earliest known codification of this law is the *Kitābi Qanī* or *Book of Qanats* which was in existence in the eleventh century.[56] Its original purpose was to protect *qanat* owners in a risky but essential investment in permanent agricultural settlement. The law of *harim* ("borders"), for example, gave the owner protection over territory surrounding his *qanat* and prohibited the sinking of new mother wells within one kilometer of existing *qanats*. As a result, large areas in the vicinity of cities like Tehran, Kirman, Sulaymaniyah, and Qandahar, where the density of tunnel-wells is high (figs. 2, 4), are closed to new settlement thereby stabilizing agricultural acreage in regions with growing populations.[57] *Qanat* owners in these cities are suspicious of deep wells and decreased flow in any *qanat* leads to immediate accusations that the nearest deep well has drained the water table.

These difficulties are compounded by the pervasive influence of *qanat* utilization on the structure and social patterning of settlements, specifically on (1) the structural organization of the settlement around this water-supply system and (2) the fragmentation of *qanat* ownership among the population. In small towns and villages watered by *qanats*, the stream runs the length of the settlement passing by or through each household compound before irrigating the grain fields downslope. Within these settlements, the location of each household with respect to the watercourse determines the quality and quantity of its water supply, and, as a result, reflects the social and economic status of its occupants. The prosperous houses of the elite are located in the upper sections where water is clean and plentiful; the poorer households of sharecroppers and laborers are located downstream where the volume of water is less and it has been polluted by use.[58] In many cases, the *qanat* enters the settlement at the house or garden of the most powerful local landlord.[59] In larger towns, this social gradient along water-supply lines is often obscured by historical development and the maze of twisting distribution channels whose every diversion is a vestige of some past business transaction, marriage, or inheritance. In short, the social patterns of many *qanat*-watered settlements are oriented to water supply and alterations in one system involve changes in the other.

Further, the ownership of *qanats* is widely diffused throughout the population, for although *qanats* are built by wealthy individuals, the constant need for repairs caused by their sensitivity to natural and social disruptions leads to rapid fragmentation in ownership. Many *qanats* have as many as two or three hundred owners and the water of some *qanats* is divided into 10,000 or more 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 thirteenth century when Hulagu Khan (the grandson of Genghis Khan) ordered that water be divided into twenty-one shares with each allotted to a certain quarter.[60] For several *qanats* in Kirman this process of fragmentation has progressed so far that the smallest owner has rights to only thirty seconds of water once every twelve days. Frequently, a water bailiff is appointed to administer the distribution of *qanat* water in time and space and it is he who settles the numberless disputes arising from its intricacies.

The *qanat* system, which once revolutionized settlement patterns in the dry lands of the Old World, is now a conservative force supporting the maintenance of existing settlement patterns and social and economic conditions. They have become through custom and law an organizing principle of traditional preindustrial society and resist change and retard new developments in its fabric. It seems likely, therefore, that *qanats* will continue to play a major role in the future economic development of settlement and irrigation in these desert regions and that they will not pass quickly into history.

SUMMARY

Horizontal wells or *qanats* were discovered in the vicinity of Armenia more than 2,500 years ago and rapidly spread to become one of the most

[56] A special assembly was convened in Khurasan in the ninth century by 'Abdullah ibn Tahir to write this book of laws on *qanats*, because in the other books on law (*fiqh*) and in the Traditions of the Prophet *qanats* are not mentioned. Ann K. S. Lambton, *Landlord and Peasant in Persia* (London, 1953), p. 217.

[57] For the case of Kirman see discussion in: Paul Ward English, *op. cit.* (1966), pp. 33, 103–104.

[58] In some cases this difference in volume can be as much as 40 per cent of the total, which severely limits the amount and kind of cash crops that poorer farmers living in the lower sections of a settlement can grow.

[59] Also noted in: George B. Cressey, *op. cit.* **48** (1958): p. 29.

[60] Ann K. S. Lambton, *op. cit.* (1953), p. 218.

important methods of dry-land irrigation in the Old World. In parts of Iran, Afghanistan, Algeria, and Morocco, this ingenious device has made human settlement possible in distinctly marginal areas. Modern technology threatens to replace the *qanat* with the more efficient deep wells, but the extent to which social and economic patterns have become enmeshed with this water-supply system will make the transition difficult.

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