WATER SCIENCE & ENGINEERING

Underground Aqueducts Handbook

"*Underground Aqueducts Handbook* offers the first synthesis on aqueducts, including those conveying water and those tapping groundwater. This is the most comprehensive review of aqueduct technology as it concerns most continents and most periods, from prehistory to the present day, thanks to a multidisciplinary approach. It underlines the necessity to preserve and reuse, or redevelop, such sustainable technologies in the global context of aridification and increasing need for water supply."

— Julien Charbonnier, Laboratory ArScAn, Nanterre, France

"...the material is well documented and convincing. Any specialist and many common readers should be interested to have this book on their bookshelf."

— T.P. Tassios, National Technical University of Athens, Greece

In ancient times, urban development required that water be transported from distant springs to centralized locations, and this practice over time further advanced the evolution of increasingly complex aqueducts. Their design and construction required knowledge of mathematics, tunneling, geomechanics, hydraulic principles, and more. These technologies are the underpinning of modern achievements in water supply engineering and water management practices.

Written by leading experts from around the world, ***Underground Aqueducts Handbook*** presents the major engineering achievements in underground aqueducts throughout history. It examines the technological developments, hydraulic features, and management practices related to the underground aqueduct technologies worldwide, and presents case studies of aqueducts from nearly 30 different countries. This interdisciplinary work includes insight into the relevant engineering, hydrology, environmental sciences, and geosciences, as well as the archaeology and history of each example. It provides valuable insights into water technologies and management with respect to durability, adaptability to the environment, and sustainability, and compares the technological developments from several regions over several periods in time.

Paradigms of these technologies and practices (not widely known among engineers) have practical application to modern-day water engineering, and help address the issues of sustainability, cost-effectiveness, and decentralization. The book emphasizes that the future trends of underground aqueducts should consider the possibility and practicality of integrating older, proven technologies into today's infrastructure.

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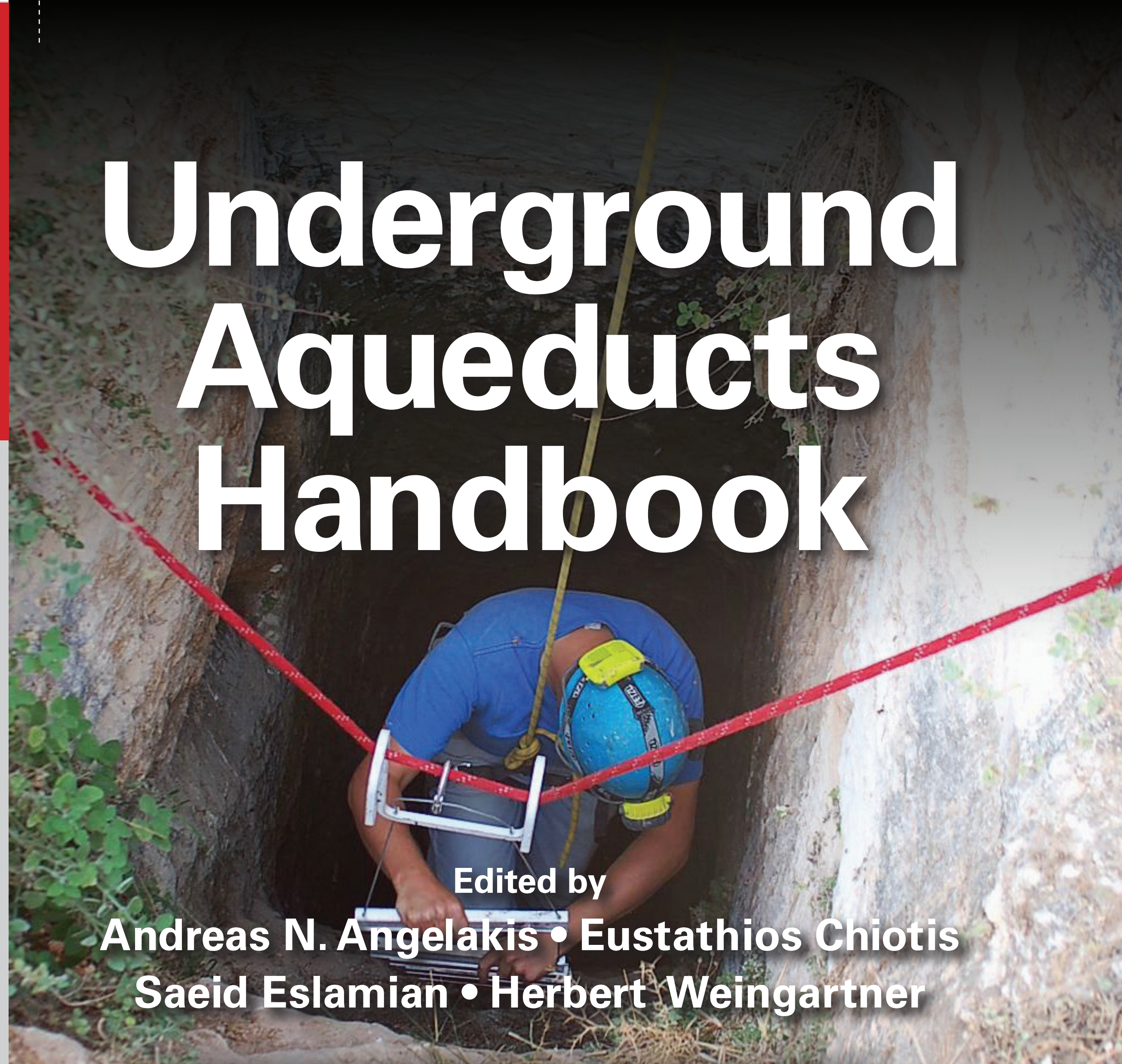
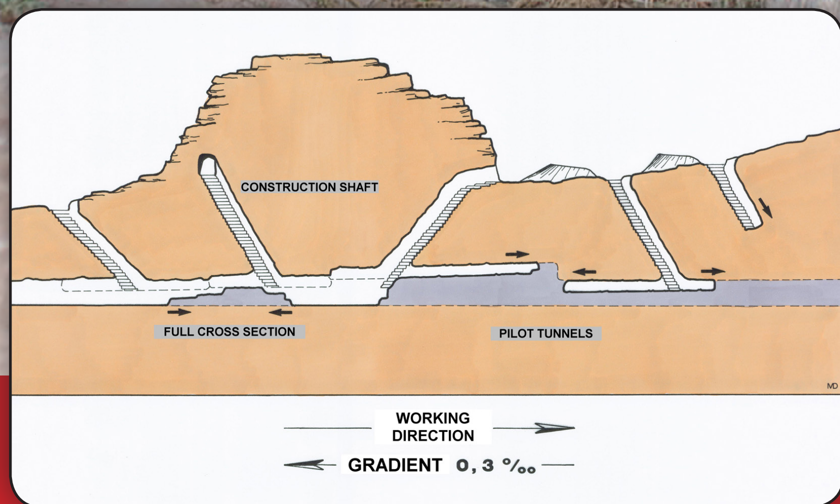


Underground Aqueducts Handbook

Edited by
Andreas N. Angelakis • Eustathios Chiotis
Saeid Eslamian • Herbert Weingartner



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Preface

The rapid technological progress in the twentieth century created a disregard for past water supply management and sustainability. In the future, urbanization will continue to increase, and 80%–90% of the future world growth (~145,000 inhabitants/day) will be in urban areas. Thus, new specific water supply technologies need to be developed, based on sustainable principles, for serving different sizes of cities and peri-urban regions. Also, many unresolved problems related to the water management principles, such as collection and transportation of water by underground infrastructures, their durability, cost effectiveness, and sustainability issues, will be intensified to an unprecedented degree, especially in the developing world.

Traditional underground hydro-technologies presented major achievements globally in the scientific field of underground aqueducts throughout the millennia. This book provides valuable insights into various underground hydraulic works, for example, qanāts (which are referred to with a particular local term in various regions of the world), tunnels, and various types of inclined galleries, with and without shafts, which transfer ground and/or surface water from an area, usually mountainous, to the lowlands—sometimes several kilometers away for use. Management issues of their characteristics of durability, adaptability to the environment, and sustainability are also considered. In addition, a comparison of the water technological developments in several civilizations has been made. These technologies are the underpinning of modern achievements in underground aqueduct engineering practices. It is the best proof that "the past is the key for the future."

This book focuses on the technological developments and management practices related to worldwide underground aqueduct technologies throughout the millennia. Paradigms of these technologies and management practices presented in this book (not widely known among engineers) may have some importance for water engineering even today. The hydraulic features of several categories of underground aqueduct technologies in numerous parts of the world are presented and discussed in this book. Finally, an attempt has been made to clarify the distinctive categories of such technologies through their historical development. In addition, potential future trends of underground aqueducts are considered including the possibility of combining old technologies with today's available infrastructure (e.g., Tunnel boring machine).

About 66 authors from several disciplines and from 4 continents and 26 counties have collaborated on this book. The disciplines include archaeology, hydrology, history, engineering, life sciences, health sciences, environmental sciences, biology, and geosciences. The geographical coverage is very wide, and it is divided into 8 parts and 29 Chapters as follows:

- Part I. Introductory (one)
- Part II. Europe (Germany, Croatia, and Greece)
- Part III. Africa (Algeria, Egypt, and Libya)
- Part IV. Middle East (Iran, Israel, Jordan, Oman, Saudi Arabia, Syria, Turkey, and United Arab Emirates)
- Part V. Eurasia (Armenia, Azerbaijan, and Kazakhstan)
- Part VI. Asia (Afghanistan, China, India, Japan, Pakistan, and Thailand)
- Part VII. Americas (Chile, Peru, and Mexico)
- Part VIII. Past, Present, and Future Trends

Finally, we appreciate the efforts and contributions of the authors who have written about the labors of humankind to bring hydraulic works to the people and cities. We also acknowledge the assistance

of the CRC Press staff, particularly of Joseph Clements and Melisa Sedler, for their professional efficiency, fruitful cooperation, useful guidance, and helpful contribution for 15 months.

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20 Ancient Water Mining in Tunnels and Wells in West Central Asia

Renato Sala

CONTENTS

The article, on the basis of the reading of the rich soviet literature on the subject, provides the first complete list of the underground waterworks of West Central Asia (which in the region are all called “*karez,*” independently from their technical variants), inclusive of their location, technical features, and documentary references. This quite tedious list is intended to be a useful tool for both Russian- and English-speaking specialists (Sections 20.1 and 20.2).

A difficulty appears when analyzing the waterworks that have an aquifer as a source. In this case, the aquifer shaft-and-gallery model (qanat) has been universally applied, disregarding the presence within the system of several elements that cannot be reduced to components of a qanat but look like infiltration wells (Section 20.3).

Therefore, it has advanced the hypothesis of the development in medieval West Central Asia of an original type of Groundwater Management System (GMS), based on Karez-GM waterwork type intended for exploiting the water of multiple shallow aquifers, where the task of building a source is prioritized above the task of catching and transporting its water. The strategy is to manage the entire aquifer-to-aquifer circulation without tunnels but by alignments of infiltration wells, until a point where water is resurged, which, in some cases, will happen spontaneously (Section 20.4).

20.1 UNDERGROUND WATERWORKS IN WEST CENTRAL ASIA: DEFINITION AND HISTORICAL BACKGROUND

The most common types of underground waterworks are horizontal tunnels and vertical wells.

A *water tunnel* is a horizontal excavation below the ground, intended for transporting surface or underground water to a chosen locale (subterranean adduction channel). Water exchanges would happen along the way, so that the tunnel, if crossing a water-bearing layer, will get recharged by infiltration (and functions as a subterranean drainage channel or as a spring-flow tunnel).

A *water well* is a vertical excavation in the ground, putting in connection the land surface with an aquifer or with overlapping aquifers.* In that way, it allows on one side the emergence of groundwater by artificial uplift or artesian pressure and, on the other side, the drainage and infiltration of surface water for replenishing the aquifer (drainage and infiltration well).

Among the underground waterworks of the archaeological record of West Central Asia, besides the huge number of single wells and a few semi-natural cisterns, several types of systems that provide the catchment and underground transport of water are documented. They can be classified into three basic types.

- Shafts-and-gallery aqueducts applied to a surface-water source (surface-water SGA, tunnel)
- Shafts-and-gallery aqueducts applied to an aquifer water source (aquifer SGA, qanat)
- Clusters and alignments of wells for management of groundwater circulation (groundwater management karez, karez-GM)

Of course, to the list must be added the case of underground waterworks of mixed type, that is, GMS coupling karez-GM and SGA schemes.

In West Central Asia, all these systems are generically called "*karez*." It is a Persian name that points to their common features: "kar" means "to draw a groove" and "rez" means "to flow," and so, the term karez means "water flow along an artificial groove." In the Sukhandarya and Nuratau regions, they are also called "kanda," a Persian name meaning "hole."†

Names, local accounts, and historical and scientific reports, all agree in affirming the Iranian origin of the Central Asian karez. The earliest historical record concerns a karez-qanat made during the tenth century AD in the Kopet-Dag, but some authors suspect an earlier Achaemenid start of the building tradition (see Section 20.2.2.1). As a whole, there is accord in attributing the start of their construction to the Early Middle Ages and their blossoming period under Shaybanid rule in the late sixteenth AD. After that time, they have been continuously in use until the early twentieth century AD, and a few are active even today.

* Overlapping aquifers are discontinuous lenses of aquifers at various elevations that are not physically interconnected.

† Actually, the term "karez" has a very wide range of possible meanings, all connected with water resurgence by aligned underground artificial structures. In Khorasan, N-Afghanistan, Bactria, and Central Asia, the term generically refers to any kind of underground waterwork characterized by vertical holes along the line, independent of the type of water source. In East Iran, it is strictly used for aquifer SGA systems, that is, as a synonym of qanat. In the Kopet-Dag, it can also mean the terminal underground or surface distributaries departing from the qanat main line, and all over West Central Asia, "Karez" is a common toponym for a village water-fed by karez structures.

Concerning the building masters, Russian geographers attribute the construction of karez in the Kopet-Dag and Fergana to Persian masters (Pendjiev 1978) and in the Nuratau to Tajik and Turkmen (Gulyamov 1979). In the Karatau, the construction of karez, is quoted by historical accounts as "dug by the work of 200 Indian slaves" and as a present from Mir-Arab, sheykh of the Sufi Naqshbandi sect of Bukhara, to his native land (Boldyrev 1976, p. 167–168) (Figure 20.1).

Besides the nationality of the karez builders, the historical records inform about their social status and tribal affiliation. It seems that the main protagonists involved in the "karez business" were the so-called "Chagatai" class and the "Khoja" tribe.

"Chagatai" is a generic name that refers to the social class of medieval Tajik or Uzbek bilingual land owners, who relied on brigades of karez builders organized as guilds.

The "Khoja" is a tribe that consists of skillful craftsmen and cunning religious entrepreneurs and is still now most widespread in whole Islamic world, particularly in Central Asia. Dissidents by nature and claiming direct descent from one of the first four caliphs or from some early saints, they have been very successful in converting Zoroastrian masters to Islam and have been the founders of three main Sufi sects (among which is the Naqshbandiya, the largest in the world). Starting from the eighth AD, they diffused to West and East Central Asia, where, after finding that the irrigation plains were already crowded, colonized the arid peripheries through the building of karez. In fact, in arid Central Asia, any tribe pretending independence must have been fit for desert colonization, which means they had a sound knowledge of water mining and, owing to the costs of the

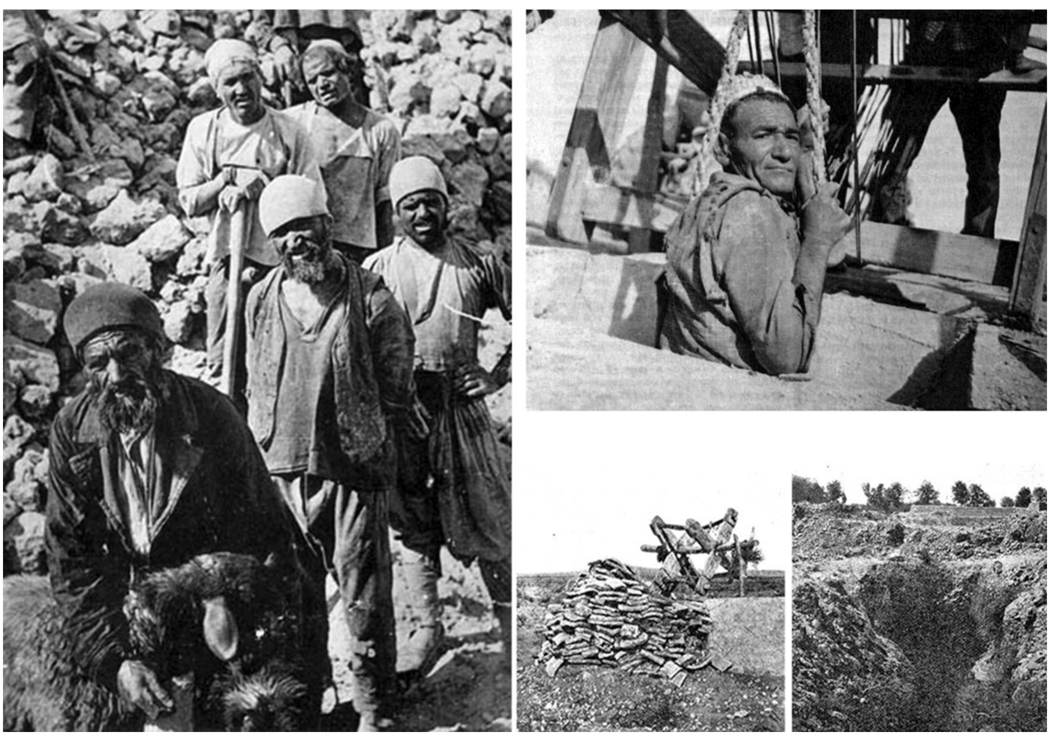

FIGURE 20.1 On the right, Persian workers in a chalk quarry near Ashgabad at the beginning of the twentieth century AD. (*From* Markov, E., *Rossiya v Srednei Azii: ocherki puteshestestviya po Zakavkazyu, Turkmenii, Bukhare, Samarkandskoi, Tashkentskoi i Ferganskoi oblastyam, Kaspiiskomu moryu i Volge* [Russia in Central Asia: Essays about travels in the Caucasus, Turkmenia, Bukhara, Samarkand, Tashkent and Fergana provinces, Caspian sea and Volga], St Petersburg, 1901, http://rus-turk.livejournal.com/138202.html.) On the left, photo of Turkmen karez master Durdy Khilliev of the Baharden oasis (From Suprunenko, V., Molchivaya voda kyariza [The silent water of the karez], *Vokrug Sveta* [*Around the World*], 60–61, April 4, 1984. With Permission.)

implementations, also good entrepreneurial capabilities. Eventually, the management of religious institutions and the building of karez became characteristic activities of the Khoja, and surely these were politically and economically gratifying activities, in that both were everywhere rewarded by property rights (waqf) and tax exemption.

Shortly, the Chagatai and the Khoja can quite correctly be considered the main developers and managers of the karez of the entire West Central Asia territory (Karmysheva 1976).

The karez of West Central Asia have never been studied systematically. Some books about ancient irrigation systems dedicate a generic paragraph to them (Bekturova et alia 2007, p. 67; Kolodin 1981). Articles specifically devoted to karez describe cases only at regional scale. In the Kopet-Dag (TM), karez are described by Nikshich, Ovezov, and Pendjiev; in the Surkhandarya (UZ) by Tursunov and Kabulov; in the Nuratau (UZ) by Gulyamov; in Usrushana (TJ) by Bilalov; and in the Karatau (KZ) by Dingelshtedt, Groshev, and Sala and Deom. The best accounts are by far the ones of Nikshich about the qanats of the Kopet-Dag and of Dingelshtedt about the karez of the Karatau region. Apart from Sala and Deom, no author suspects the existence of karez without gallery.

The present documentation concerning karez is based on: historical accounts; geographical, ethnographical, and archaeological reports; toponymy of villages and locales (Karez, Kariz, Karizsai, Karizstau, Dolina Kariz, Korez, etc); and satellite images.

20.2 KAREZ OF WEST CENTRAL ASIA: GEOGRAPHICAL LOCATION BY TYPE

As a whole, in the West Central Asia expanses, the presence of karez of any type is documented in eight regions (Kopet-Dag, N-Bactria, Zeravshan, Nuratau, Usrushana, Ahangaran, Fergana, Karatau, and Talas), with the highest concentration occurring in the Kopet-Dag, Surkhandarya, Nuratau, and Karatau regions.

The three main types of karez spoken above differ by technology and geographical location.

- *Shafts-and-gallery aqueducts* (SGA) are underground waterworks intended for catchment and underground gallery transport of water from a water source. They have three main elements: the water catchment head, depending on the type of water source; a sloping tunnel connected to the land surface through a series of vertical holes (shafts, which can be absent in case of very short length), from which comes the system's name; and the final outlet (mouth). The water source can be of two types: surface water (a river, a spring [spring-flow tunnel], or a canal) and aquifer water; similarly, the SGA can be of two types: *surface-water SGA* (*tunnel*) or *aquifer SGA (qanat)*. The geographical diffusion in West Central Asia of surface-water SGA and aquifer SGA is in both cases reported in four regions and is described in Sections 20.2.1 and 20.2.2.
- *Groundwater Management karez (karez-GM)* are underground waterworks intended for the management of groundwater circulation through the digging of clustered and aligned wells and the use of fossil riverbeds. Their geographical diffusion in West Central Asia is documented in six regions and is described in Section 20.2.3. Their technical aspects are quite original and will be discussed in Sections 20.3 and 20.4.

Quite understandable are the patterns of the geographical distribution of the different types of karez in the West Central Asia territory. Karez are present in different densities along the piedmonts of all mountain massifs, from the Kopet-Dag to the Pamirs and the Tienshan. Tunnels intended for the transport of surface water are found in the mountain zones where rivers are still active. Instead, groundwater structures (qanat and karez-GM) are established on the piedmonts of the westernmost and most arid mountain ranges (Kopet-Dag, Surkhandarya, Nuratau, and Karatau), where the extreme water scarcity justifies higher labor investment in groundwater structures (see Table 20.1 and Figure 20.2).

TABLE 20.1
Karez of West Central Asia: Location, Type, Number, Technical Features, and Chronology

Region	Type & N°	Asl (m)	Geo Morphology M = Mountain F = Foothill P = Plain (%)	Slope (%)	Water Source C = Canal R = River S = Spring A = Aquifer (%)	Length Total/ Approximate (km)	Vertical Holes Distance Interval (m)	Vertical Holes Depth (M)	Water Outflow (L/s)	Start-End Centuries AD[a] (Builders)
Kopet-Dag	Tunnel 10?	–[b]	F P	–	R	–	–	–	–	10–21 (Iranian, Turkmen)
	Qanat 1100	400–150	M5 F60 P35	4–0.5	R25 S20 A55	1100/1	25	25–2	2–40	
Surkhandarya	Qanat 30	700	F60 P40	1.4–0.4	R30 S30 A30	40/0.7	15	–	8	10–20 (Tukmen, Chagatai)
	Karez 200?	900	F	–	A	60?/0.3	5–7	–	–	
Zeravshan upper	Tunnel 36 karez	1200–1000	M	4	C	7/0.25	20	–	–	15–19 (Tajik)
Nuratau Central	Qanat 8?	530	F	7	A	4.5/0.6	12	<25	–	10–20 (Tajik, Turkmen)
		450	P	0.4						
	Karez 360	800–350	M5 F10 P85	0.5	R20 S10 A70	200/0.8	15	15?	20	
Nuratau North	Karez 3	970–430	F	1–0.5	R30 A70	3/1	15	<25	–	12–19 (Tajik, Uzbek)

(*Continued*)

TABLE 20.1 (*Continued*)

Karez of West Central Asia: Location, Type, Number, Technical Features, and Chronology

Region	Type & N°	Asl (m)	Geo Morphology M = Mountain F = Foothill P = Plain (%)	Slope (%)	Water Source C = Canal R = River S = Spring A = Aquifer (%)	Length Total/ Approximate (km)	Vertical Holes Distance Interval (m)	Vertical Holes Depth (M)	Water Outflow (L/s)	Start-End Centuries AD[a] (Builders)
Usrushana W	Karez 200?	1950–470	P	0.6	–	–	10–12		–	12–19 (Tajik)
Usrushana E	Tunnel 25	470	M F P	0.01	R	12/0.5	5–8	20–7	–	
Fergana N	Qanat 9	750	F	0.4	A	0.04	15–20	6	10	18–20 (Persians)
Karatau South (Sauran)	Karez 260	320–200	F60 P40	0.4	A	123/0.47	15	4–3	–	10–19 (Uzbek, Indians)
Karatau South (Turkestan oasis)	Karez 30	450–200	P	0.4	A	15/0.5	15	4–3	–	16–19 (Uzbek)
Talas upper	Tunnel 2	1300	M	0.8	R	0.4–0.2	15	–	–	7–10
	pipe 2	1700–1500	F	5	S	10–5	–	–	–	

[a] The chronological attributions are based on historical accounts and on unverified correlation with the surrounding archaeological complex.

[b] Data not available.

FIGURE 20.2 Map of the geographical location of underground waterworks by type. (tunnels, qanat, and karez-GM) in West Central Asia (Courtesy of JM Deom).

20.2.1 Surface-Water Shafts-and-Gallery Aqueducts (SGA) (Karez Tunnels)

The simplest and the most diffused type of surface-water SGA is represented by the underground segment (a tunnel with or without shafts) of an open canal transporting water from a surface source (river or spring). In West Central Asia, tunnels of this kind are not very numerous, and just around 100 cases distributed in four regions are known to the author.

20.2.1.1 Kopet-Dag, Region (TM)

Two sets of water tunnels are documented in the plains west of the Kopet-Dag range, along the *Sumbar* river, and in the *Chardzhou* region (Kodjakenepsi), near the left bank of the mid-Amudarya course, respectively. In both sites, these tunnels are segments of canals that transport river water to fields. On the Sumbar, a few short tunnels without shafts are excavated in the rocky cliffs of narrow passes: they are called "sum." Around Chardzhou are found five tunnels with shafts; their type is of Iranian origin and is called "*lagym*" (which means "tunnel") (Pendjiev 1978).

20.2.1.2 Zeravshan, Upper Valley (TJ), and Plains (UZ)

Here, the presence of surface-water SGA is documented in the mountain zone of the upper valley and in the plains.

- In four different areas of the upper valley (Penjikent, Aktam, Cherbak, and Kshtut), 36 tunnels are quoted as still active at the end of the nineteenth century. They are underground segments of canals from the Magyandarya river, a few hundred to 1000 m long, and are provided with vertical or horizontal shafts. Their construction is attributed to a leader of the Nakshbandi Sufi school during the fifteenth century AD (Arendarenko 1889, p. 162). In particular, one must quote a "karez" at Cherbak, which departs from a canal paralleling the river bed and develops for 3 km with 90 shafts, of which the construction is attributed to the Kharakanids (tenth to twelfth century AD), evident by a stone inscription located at the "mother well" (or, better, "at the first shaft") (Fedchenko 1870).
- Concerning the Zeravshan plains, archaeological studies proved that in the Medieval time, the sardoba (water cistern) of the caravanserai of Rabat-i-Malik (near Navoi) was supplied by surface-water SGA from the Zeravshan river (Nemtseva 2009). Moreover, north of Navoi, on the southeastern slopes of the Aktau range, in the east of the Aksai river and of Aktepa village, the presence of a canal with several tunneled short segments (a type that all over Uzbekistan is called *qon-aryk,* buried canal) is documented; it is 6 km long, with a total of 600 shafts, and is dated to the sixteenth century AD (Hasanov 2014).

20.2.1.3 Usrushana, Eastern Part (TJ)

Here, around 25 tunnels, distributed in 3 parallel valleys are documented: 8 tunnels in the Basmanda valley, 7 in the Aksu, and 9 in the Hoja-Bakyrgansai. All of them consist of the underground segment of a canal, with length from 50 to 1500 m and horizontal or vertical shafts, the last sometimes of relevant depth. Some tunnels have been built in the Middle Ages, and most of them were still active at the beginning of the nineteenth century AD (Bilalov 1980). Three tunnels ("karez") at the end of the Aksu valley are relevant for their size and for the legends that surround them, all located 1–2 km far from each other, nearby the Tagoyak village.

- The Tagoyak karez, at the western limits of the Tagoyak village, is 1 km long, with vertical shafts 7–40 m deep, and, in the fields, their mouths are protected by a metallic enclosure. It was restored before the Soviet period, and its final outlet provided of a cement vault shaped as a mausoleum (Figure 20.3).

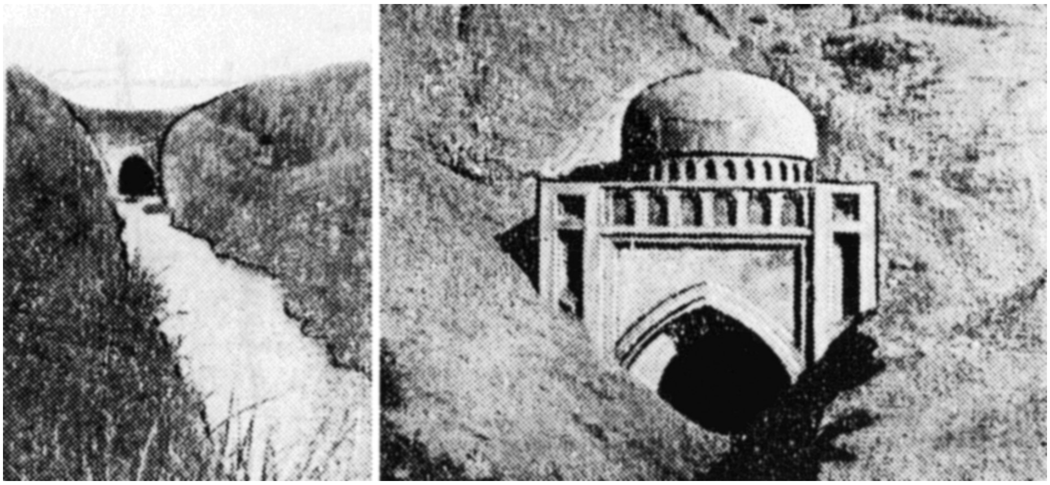

FIGURE 20.3 Mouth of the Tagoyak karez, Aksu valley, Usrushana (UZ). GPS coordinates: N40°07′16.43″ E69°18′56.31″. (From Bilalov, A.I., *Iz istorii irrigatsii Ustrushany (Materialnaya kultura Ustrushany, vyp. 4)* [From the history of the irrigation of Ustrushana (Material culture of Ustrushana, issue 4)], Doshin, Dushanbe, Tajikistan, 1980. With Permission.)

- The Shirin karez, which is 1.3 km north of the last, but not anymore detectable on the land surface, is described as pointing to the medieval town of Shirin-tepe, with unfinished shape and without visible head or end. It just consists of a 200 m long line made of only four vertical shafts having depth of 8–20 m, mouths of 4 m in diameter, and mounds 20 m large and 4 m high. A legend pretends to explain its mysterious shape.*
- The Kallakhon karez, located on the opposite right bank of the Aksu river, is 1.5 km long, with very low declivity (0.12 m/km), carrying water of the canal "Shavkataryk" from Tashkuprik village to the medieval mound of Kallakhon. It was still active in 1970. According to a local legend, the Shavkataryk canal is very old, traced in the twelfth century AD by the younger brother of Ahmed Yasawi, Abdurakhman Bekhtar Bashi, whose mazar preserved during three centuries the big bronze cauldron that now stands at the entrance of the Yasawi mausoleum in Turkestan.

20.2.1.4 Talas, Upper Valley (KG)

Two cases of underground water transport are found within the large medieval urban system of the *upper Talas* valley (Northern Tienshan), which grew in the quite arid landscape of the bottom valley (precipitation is less than 400–300 mm/y) but at the center of a very rich mining complex. The first case consists of two stream-side tunnels carrying the waters of a mountain stream to a metallurgic town surrounded by freshwater springs; the second case consists of two buried pipelines carrying fresh springwater to a metallurgic town reached by a channeled paleo-course of the Talas river.

* The legend relates the story of Shirin, the daughter of a local dekhkan (landlord), whose beauty attracted two lovers, Chosrov and Farkhad, pretending her hand. Shirin challenged the pretenders to irrigate the lands of the Kurkat valley (5 km west of the Aksu valley) and promised to marry the first who would achieve this task. Farkhad decided to build a dam on the Syrdarya and bring water through canals. Chosrov chose for a karez from the Aksu river; however, after some time, seeing the amount of unfinished work and the proximity of the deadline, he settled for a ruse. On a full moon night, he put down a track of straw mat shining like a stream from the Aksu river to the tepe. At the view of the success of his rival, Farkhad in despair drowned himself in the Syrdarya, and the next morning, Shirin, seeing that she had been cheated, resolved to follow Farkhad, drowning herself in the same river. This legend might reflect the unfinished shape of this line but doesn't explain the fact that the mounds piled at the shafts' mouth are too high and could only be accumulated during some centuries of gallery cleaning.

- Two parallel tunnels around 200 m long and with horizontal shafts are dug at different elevations in the rocky cliff of the right shoulder of the mouth of the Urmaral river valley, a left tributary of the Talas river, where it merges 16 km further north. The tunnels provide way for two open canals (of a system of four), catching and transporting the Urmaral river waters at different heights and feeding the fields surrounding the medieval town of Aktobe-1 (Orlovskoe, 5.58 ha, seventh to fourteenth century AD). The Urmaral valley, with 11 important mining points, represents one of the richest mining zones of the Talas valley, and Aktobe-1 is one of its five earliest and most enduring walled towns and metallurgic centers, surrounded by abundant freshwater springs but unconnected with the Talas river waters (Kozhemyako 1963; Sala and Deom 2016).
- On the slopes of the same left side of the Talas valley, 30 km upstream, where water resurgence becomes more scanty, the freshwater of a set of premountain springs of the Beshtash-Kolba interfluve is caught at 1700 m asl and conveyed 4 km down to 1500 m asl by two parallel clay water pipes buried underground. They end in the surroundings of the early metallurgic town of Kashkantobe (5.17 ha, seventh to twelfth century AD), which is facing a mountain zone hosting several mining points and is deprived of neighbor springs but reaches by a reworked distributary from the Talas river 4 km away (Sala and Deom 2016).

20.2.2 Aquifer SGA (Karez-Qanat)

The second and third types of karez listed above (Section 20.2) have groundwater as source; both represent soft sustainable ways of groundwater mining, but their techniques are quite different. Aquifer SGA (qanat). In this case, the aquifer water is caught by a mother well (or by the tunnel itself) and transported by a gallery with shafts. In Central and West Iran, such structures are called “qanat” (an Arabic name meaning “channel”), and in Central Asia, they are generically referred to as karez. Groundwater Management karez (karez-GM). In this case, the aquifer water is conveyed to emergence not from a mother well though a gallery but from aquifer to aquifer through a complex system of wells. This type of underground waterwork is the most diffused in W-CA.

From the land surface and satellite images, both types of aquifer karez appear quite similar as a line of vertical holes, which can be shafts or wells. In the first case, with mounds generally larger and more outdistanced, they correspond to the shafts of the gallery of an aquifer SGA; in the second case, they correspond to the wells of a karez-GM system.

The main advantage of these groundwater mining systems consists of providing, if not a constant, at least a continuous water outflow, which is the indispensable prerequisite for agriculture where summer rains are absent (at the price of a certain water waste during the winter season). Therefore, their technology diffused in arid regions deprived of summer precipitation, playing the major role in the colonization of dry interfluves and arid peripheries of fluvial irrigation valleys. Here, they are built on gently sloping piedmonts located below well-watered mountainous terrain, best on alluvial cones covered by a thickness of unconsolidated regolith deposits (soil, alluvium, etc) that are very conducive to infiltration and aquifer formation (Planhol 2011).

West Central Asia is an arid landlocked territory. Water resources are scanty and concentrated in the mountain and piedmont zones, consisting of ice deposits, springs, rivers, endorheic lakes, and ponds. In most of the arid plains, the only available water resource is groundwater.

This is particularly true in the case of Kazakhstan. Here, more than elsewhere, during the last 3000 years, the entire territory with all its landscapes, from mountain meadows to deserts, has been concerned and trodden by pastoralist activities; however, at the same time, the total renewable freshwater resources amounts to just $23 \times 10^6 m^3$ per km^2, against the 230 of Turkmenistan, 110 of Kyrgyzstan, and 100 of Uzbekistan. Therefore, in the most arid zones of West Central Asia and particularly of KZ, owing to the scarcity of surface water, among the different types of waterworks, by far, the most common are the ones applied to an aquifer source.

Aquifer SGA systems (qanat) are described below (in Sections 20.2.2.1–20.2.2.4)* and karez-GM systems in Section 20.2.3.

On the basis of the historical sources and archaeological reports, in West Central Asia, the identification of classic qanats has been proved in four regions: more than 1100 samples have been documented in the northern piedmonts of the Kopet-Dag range, around 30 in the Surkhandarya, a few samples around Nurata town in the Central Nuratau region, and just 9 in the northern part of the Fergana valley.

A variant of aquifer SGA is represented by the case when the mother well is absent and groundwater is caught by infiltration in the tunnel itself (spring-flow tunnel). Generally, in this case, the tunnel is an underflow channel developing along a river bed and draining water from shallow aquifers formed by seepage from the water course; or, it crosses transversally parallel riverbeds or trains of alluvial fans; or, it is a side tunnel applied to the main qanat line in fish-bone patterns. In the Kopet-Dag, half of the aquifer-SGA are provided of mother well and half catch groundwater as a spring-flow tunnel; in the other regions, most of the aquifer SGA seem to be of spring-flow tunnel type.

20.2.2.1 Kopet-Dag, Northern Piedmonts (TM)

All along the northern slopes of the range, more than 1100 classic qanats, with or without mother-well and between 1500 and 5500 m long, are documented. Most of them are concentrated on the 10 largest alluvial fans of the piedmont band stretching for 130 km between the Bereket valley in the NW and the Ashgabat valley in the SE, with the highest density in the Baharden, Yaraja, Geoktepe, and Ashgabat valleys. East of Ashgabat, they are found in lesser number, until the Tedzhen and Murghab deltas. They are called karez by the local population as well as in scientific reports (Figure 20.4).

Many Russian geologists, hydrologists, and ethnographers provide the description of the Kopet-dag karez-qanat. In their typology, all authors classify karez-qanats by water source (river, spring, or aquifer), by shafts' depth (shallow [10 m], not deep [10–20 m], average [20–30 m], or deep [30–50 m]), and by outflow (very weak [<3 L/s], weak [3–10 L/s], average [10–30 L/s], or abundant [up to 100 L/s]).

The best scientific account is given by the hydrogeologist I. Nikshich, who surveyed 110 qanats, and of 78 of them provided information about location, water source,† length, shafts' number and depth, and outlet. In the entire region, in 1920, 200 qanats were still active, with a total outlet of 2260 L/s; in 1965, 98 qanats, with a total outlet of 1140 L/s; in 1970, around 54 qanats were still in use, with a total outlet of 1000 L/s.‡ In just the Ashgabat district, in the early 1890s, 17 short qanats, with a total of 140 wells (30–40 m apart from each other), were still in use; and till 1940, four major qanat systems were bringing water inside the city. One of the biggest qanat lines near Ashgabat was the karez-Ishan,§ with a length of 5200 m, a mother well of 52 m depth, and an abundant outlet of 40 L/s (Nikshich 1924, p. 99).

Ethnographic and historical information about them is provided by M. Pendjiev (1978) and M. Ovezov (1973). The last one supports their Achemenid origin, which is also proposed by the historian V. Barthold, notwithstanding the fact that the oldest historical record of a Kopet-Dag qanat refers to a line of the Kyzyl-Arvat region, dated to the tenth century AD.

* In the entire world, the total number of karez qanat, which in the last 50 years decreased by half, still provides a total outflow of 430 m^3/s, which is enough for irrigating 1.5 million ha, that is, the 0.6% of the total irrigated areas. The 60% of them are located in Iran, the 25% in Afghanistan, and the 10% in Oman.

† Nikshich and Ovezov agree in pointing always to an aquifer as their water source: an aquifer near a spring, under a riverbed, or far from both.

‡ See "Ghidrogeologhia CCCP (Hydrogeology of SSSR)," 1972.

§ The important karez lines always deserve a proper name, and the last is always a Persian name.

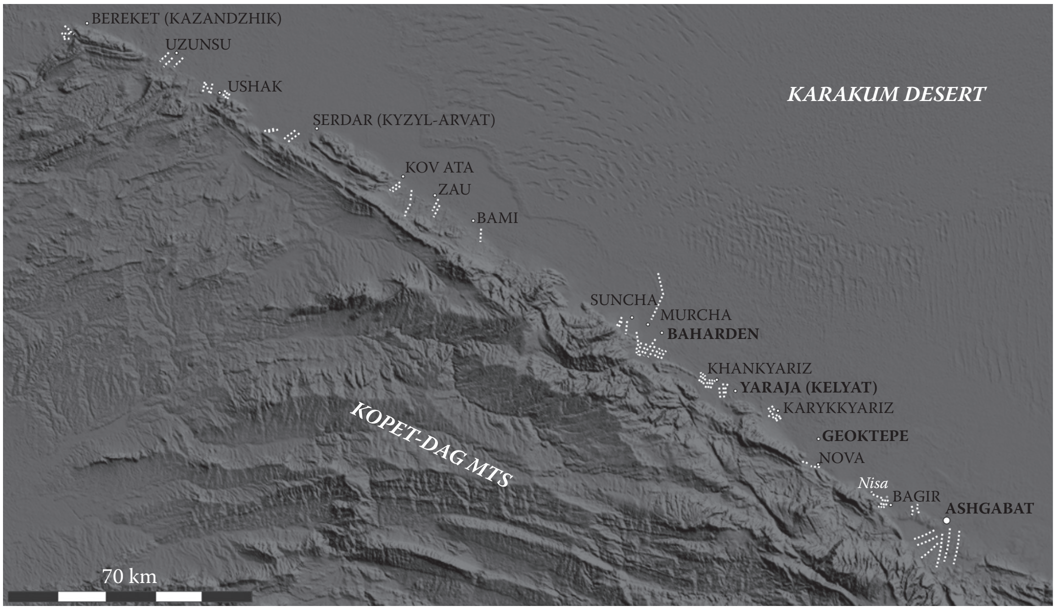

FIGURE 20.4 Map of the qanats of the northern piedmonts of the Kopet-Dag (TM). White dashed line: qanat. (on AsterGDEM image, GlobalMapper.)

20.2.2.2 Northern Bactria, Surkhandarya Valley (UZ)

In the *Surkhandarya* valley, the best preserved lines of karez-qanat are located in its SW part, on the eastern foothills of the Kugitangtau mountains, with the highest concentration on a piedmont band developing for 20 km between the villages of Pashkhurt and Charvak. Already documented in 1876 by the army journalist N. Maev (Kabulov 2015, p. 10), they consist of around 25 lines, most of them still clearly visible on satellite images. They have been interpreted as typical qanats of foothill type, starting from an aquifer of the upper alluvial fan in a sloping environment of 5%, with average length of 700 m and max length of 3 km, shafts 15 m far from each other, and an average depth of 15 m. The outflow has been estimated from 4 to 50 L/s and reaches a peak of 80 L/s during springtime (Nazarov 2015, p. 123).

In the northern periphery of the complex, the presence of several karez-GM and of mixed-type karez systems is suspected (see below, Section 20.2.3.1) (Figure 20.5).

20.2.2.3 Nuratau Range, Central (UZ)

The Nuratau range is made of two parallel mountain groups: the Nuratau range on the North and the Karatau-Aktau ranges on the South. The Central Nuratau region is located between the two ranges spoken above and consists of two large parallel valleys developing East to West: the Selsai valley, 80 km long (the richest in karez lines, mainly of Karez-GM type; see below [Section 20.2.3.3]), and, on the south of it, the Arasai valley, 50 km long.

In the SE part of the Selsai valley, around the Dzhush village, the Russian geographer Radlov quotes in 1880 the presence of an ‘artificial river’ made of 8 lines of wells connected by deep underground galleries (Radlov 1880, p. 9). In the SW part of the Selsai valley, in the surroundings of Nurata town, the ethnographer N. Dingelshtedt recorded in 1889 the functioning of some karez lines with gallery (aquifer SGA, qanats), each line averaging 30–250 shafts, 12 m far from each other. The longest among them was counting 300 shafts, reaching 25 m of max depth, and its yearly maintenance was provided by 4–6 working months of a brigade of 30 peoples (Dingelshtedt 1889, p. 281).

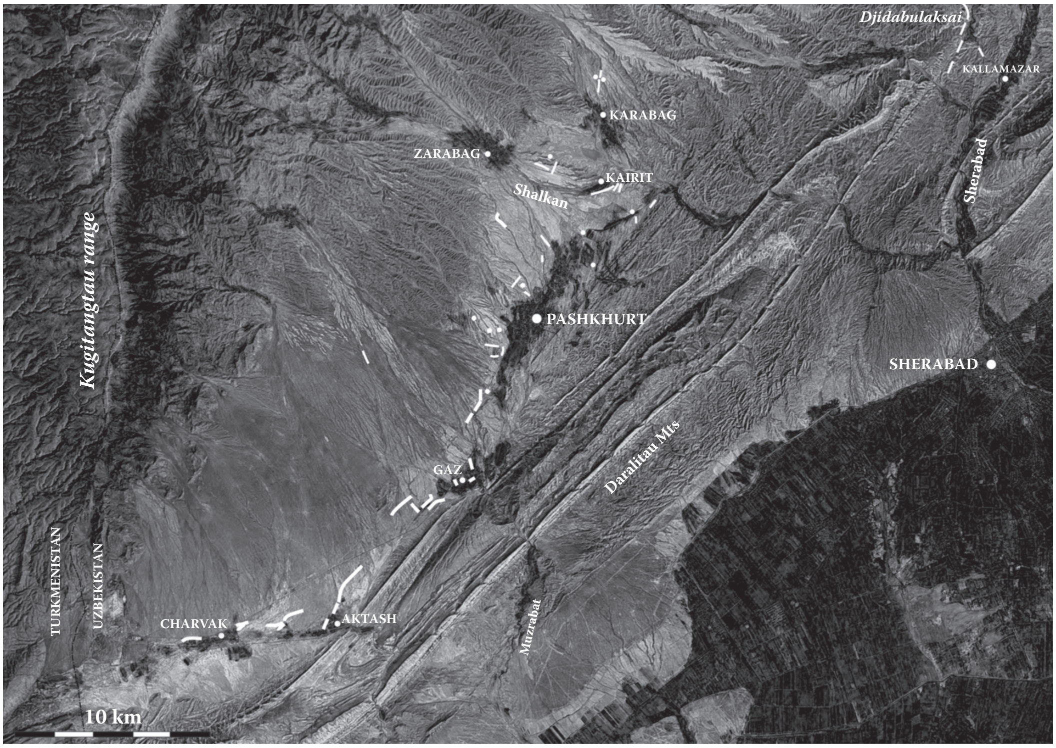

FIGURE 20.5 Map of the qanats of the Surkhandarya valley (Sherabad district, UZ). White thick line: qanat; white thin line: karez-GM; white dots: cluster of wells. (on satellite image, SAS.Planet.)

Recent surveys by part of Uzbek geographers documented a qanat line at the southern limits of Nurata town; it is named “karez-kalta” and is 600 m long, with 62 shafts going from 40 (doubtful data) to 5 m deep[*] (Hasanov 2014).

20.2.2.4 Fergana Valley, Northern Part (UZ)

In the *Namangan* region, along the Namangansai river, nine karez-qanat lines have been found around the villages of Guldirav and studied by archaeologists in the 1986, but today, they are poorly visible on satellite images. They are reported as having average length of 40 m, shafts’ mounds of 4–10 m in diameter, and an underground tunnel transporting the groundwater of a shallow aquifer, with water table at the depth of 5–6 m. Each of these short lines had an average outflow of 10 L/s, irrigating 10 ha of land. According to the local inhabitants, these qanats were built during the eighteenth to nineteenth century AD by Persian immigrants (Abdulkhamiddov et al 1987).

20.2.3 Groundwater Management System (GMS)

Karez of karez-GM type, where the aligned vertical holes do not correspond to shafts of a gallery (that does not exist) but to wells for groundwater management, have been archaeologically studied only in one region (Karatau) and are suspected wherever the identification of qanat SGA has not been successful. In that sense, they are the most diffused underground waterworks of West Central

[*] South of Nurata, where the slope’s inclination is of 3.5%, a qanat line 600 m long cannot have a mother well deeper than 10–15 m. If so, the referred qanat could correspond to one of the eight lines visible in the area, possibly the one with GPS coordinates N 40°32′40.62″ E 65°41′54.41″.

Asia, documented or suspected in six regions, and particularly numerous in the Surkhandarya, Nuratau, and Karatau, waiting for hydrogeological and archaeological investigation and confirmation. Isolated short lines have been also detected in peripheral areas.*

20.2.3.1 Northern Bactria (UZ, TJ)

In this region, the presence of karez-GM systems has been documented or suspected in three parallel valleys at the south of the Hissar range: Surkhandarya, Kafirnigan, and Kyzylsu.

- In the SW part of the *Surkhandarya valley*, 15–30 km north of the area, where qanats have been documented (Section 20.2.2.2), in some right-tributary valleys of the Sherabad river, recent investigations discovered hundreds of karez lines that, when compared with the ones of the local qanats, appear shorter and with vertical holes smaller and two times nearer, which as a whole makes one suspect the presence of karez-GM type systems (Stančo 2009). These karez lines are most often located in elongated depressions and are surrounded by clustered wells and collector canals, as if intended more for replenishing than for redirecting functions (see Sections 20.4.1 and 20.4.2; Figures 20.5 and 20.9).
- In the *Kafirnigan valley* (TJ), in the SW part of the basin, on the southeastern foothills of the Babatag mountains (Bishkent valley), karez must have once been numerous, as testified by toponyms and archaeological reports (Mandelshtam 1966), but today, they are no more detectable on the land surface.
- In the *Kyzylsu* basin (TJ), reference to the possible presence of karez is provided only by the toponymy of a few villages in the mid valley of its two tributary streams, Tairsu and Yaksu.

20.2.3.2 Zeravshan, Upper Valley, and Plains (TJ)

Along the low course of the *Magyandarya*, a left tributary of the Zeravshan river, beside the number of underground tunnels quoted above (Section 20.2.1.3), some short karez have also been realized in order to increase the water stock of the canals (Fedchenko 1870).

A few karez lines have also been recently documented in the southwestern periphery of Samarkand, in the piedmont plains of the western spurs of the Zeravshan range (Shishkina and Inevatkina 2012).

20.2.3.3 Nuratau Range (UZ)

As said above, the Nuratau range consists of the Nuratau and Karatau-Aktau ranges. Here, three regions must be distinguished: Nuratau Central, between the Nuratau and Karatau-Aktau ranges; Nuratau Southern, on the southern slopes of the Karatau-Aktau; and Nuratau Northern, on the northern slopes of the Nuratau. In all of them, the presence of karez has been documented.

- *Nuratau Central*. The region consists of two large parallel valleys, developing East to West: the Selsai valley, 80 km long, and, on the south of it, the Arasai valley, 50 km long. A total of 200 karez lines have been documented, averaging 1 km in length and stretching all together for total 200 km.

  The most crowded is the Selsai (Kalamadjar) valley, hosting 161 lines: 130 are paralleling and/or succeeding each other along and even inside the dry riverbed of the Kalamadjar

* We describe below just two samples of peripheral karez:
In the southern Kyzylkum desert, 165 km north of Nurata town, on the southern slopes of the Tokhtatau low-mountain range, a village called Karis is fed by two 300 m long karez lines dug into a fossil riverbed.
A single karez line 300 m long, representing the remotest karez-GM of West Central Asia, has been documented in the Anrakhai region of SW Balkhash. It is intended for filtering and purifying the water of a pond and channeling it to the late Medieval Kalmyk Fortress of Kalmaktobe 0.20 ha, seventeen to eighteen centuries AD. (see geographical location in Figure 20.2.1, number 19)

stream (see below, Figure 20.10); 20 are along its 2 upper tributaries; and 11 are located on the piedmont slopes at the south of the valley, of which 2 are at Chuya and 8 are south of the medieval town of Nurata (where N. Dingelstedt reports the presence of some qanat lines; see Section 20.2.2.3). The Arasai valley hosts 39 lines around the Gazgan village, on the piedmont slopes of its northern side (Figure 20.6).

These karez have been recorded by historical sources,* ethnographic documents,† and geographical and archaeological reports.‡ Moreover, their presence is witnessed by numerous villages' toponyms and local accounts, and they are detectable on satellite images, with impressive clarity.

- *Nuratau South*. On the southern slopes of the Aktau-Karatau range, in the Karangulsai valley, karez have not been surveyed, but their presence is suspected on the basis of villages' toponyms and by the detection of 10–20 short lines, with wells 5 m far from each other, on satellite images.
- *Nuratau North*. On the northern foothills of the Nuratau range, on the basis of archaeological reports, toponyms, and satellite images, the presence of karez is documented at three sites (Mukhamedzhanov 1969). The archaeologist S. Suyunov studied several karez lines in the easternmost site (Farish district). He does not mention the presence of any gallery but describes the vertical holes of one line that has source in the fossil bed of the Suloklisai (Sulaklisai) river; holes are at intervals of 15 m and have depth varying from 25–20 to

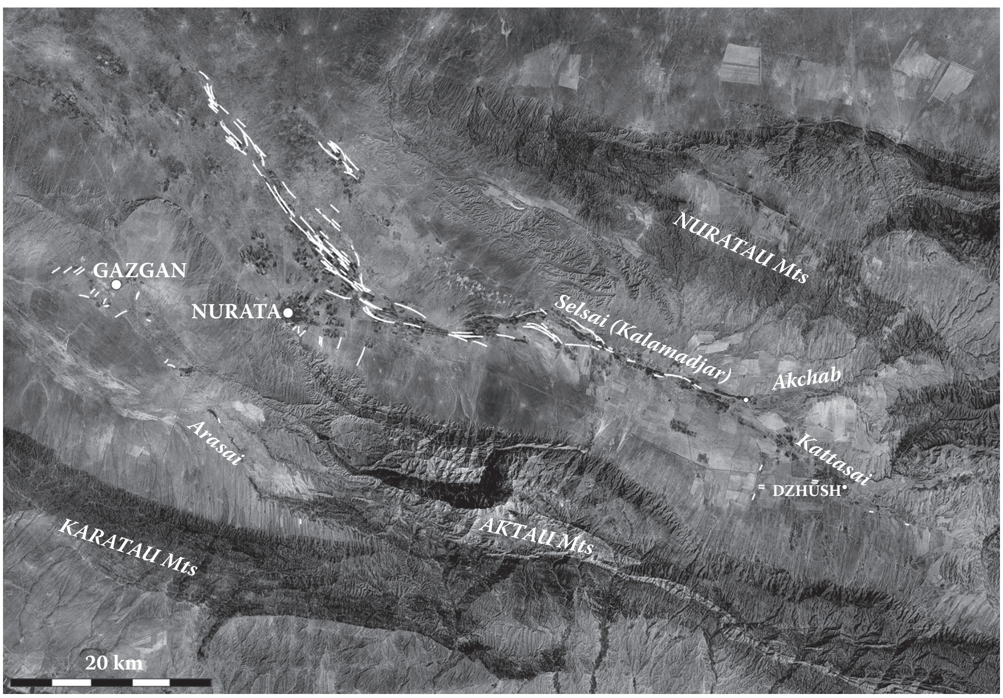

FIGURE 20.6 Map of the karez of Central Nuratau (UZ). White line: karez-GM. (on satellite image, SAS. Planet).

* These karez are quoted in diplomas dated at the times of the Djuibars sheiks (sixteenth century AD) where their professional builders are called "karizgher".

† The Uzbek specialist in irrigation archaeology YJ Gulyamov, in his article "Nur Bukhaurskii", wrote: "According to the sayings of the local mirabs, in the past there were 360 karez in the Nurata steppes"… The names of some of them, like "Zulim" or "Zulfiqar," reflect the date of their building: the firsts in 1563 AD, the seconds in 1696. Only few of these karez are still in use because the local population prefers using modern pumps for irrigation." (Gulyamov 1979).

‡ See (Nizomov 2008) and (Nazarov et alia 2015).

4–2 m; the best preserved one has a mouth with diameter of 1.3 m and a mound 1.65 m high. He dated the karez on the basis of the surrounding medieval settlements to the eleventh to twelfth century AD (Suyunov 1999, pp. 11–12).

20.2.3.4 Usrushana, Western Part (UZ)

Usrushana is the region located north of Samarkand, between the Turkestan range and the Syrdarya river. Here, besides the surface-water SGA of the Basmanda and Aksu valleys in the Usrushana's eastern part (quoted above, Section 20.2.1.3), the historical presence of groundwater karez is documented in two areas of its western part: on the northern piedmonts of the Turkestan range (Sanzar valley) and in the immediate following plain, which for its aridity is called "Hunger steppe" (Bilalov 1980). Today, only a few lines are visible.

- In the upper *Sanzar* valley, around the village of Nauka, in 2011, some technical works brought to light the segment of an unidentified underground structure consisting of a 15 m long gallery dug at a depth of 15 m, reinforced by a wooden frame and provided with one vertical shaft (Pardaev et alia 2012). In the lower Sanzar valley, around 23 km upstream from the town of Jizakh, the historical presence of several hundreds of karez lines is documented, each averaging 300 wells or more (Bekturova et alia 2007, p. 70), of which today only a few can be identified.* Of this area, the Uzbek archaeologist Suyunov describes an archaeological complex made of 1 medieval town (Kurgan-tepe, second century BC to eighteenth century AD); 21 medieval villages; 2 karez lines 1.5 km long, dated to the sixteenth century AD; and around 5000 ha of irrigated land (Suyunov 1999, p. 14).
- The "Hunger steppe" is famous for its dryness and its huge medieval and soviet complex of irrigation networks that catch water from the Syrdarya river. In its southern part, out of reach of irrigation canals, the presence of karez is quoted by relatively old reports, and a few lines can be detected on satellite images today. According to NP Petrovski (1894), at the end of the nineteenth century, all area at the west of Dashtabad (Ulyanovo) was "full of remains of karez with their wells recognizable on the surface by their funnel-shaped depression"; and the karez on the alluvial fan of Akbulak had been freshly restored around 1880 by the Kyrgyz (Kazakh) Mulla Ismankul (Bilalov 1980, p. 33).

20.2.3.5 Ahangaran Valley (UZ)

In the Chach region, south of Tashkent, on the left bank of the Ahangaran river (an historical mining district), the presence of karez is just suspected on the basis of the high number of toponyms.

20.2.3.6 Karatau Range (KZ)

Karez are detected in the southern slopes of the Karatau range, in 5 of the 10 valleys of the Turkestan oasis, and, on the basis of the Dingelshtedt report (Dingelshtedt 1889, pp. 280–290), a few lines must be present on the northern foothills of the range, in the surroundings of the medieval town of Suzak.

- By far, their main concentration is found in the basin of the westernmost valley, the one of the Tastaksai, Aksai, and Maidantal rivers (TAM), where the medieval town of Sauran is located.† Here, 261 karez lines (interacting within 47 karez systems), with an average length

* Today, here, like in many other places, most of the karez have been opened and transformed into aryk (canals) and can't be seen anymore on the land surface or in satellite images.

† Sauran is a Late Medieval (thirteenth to eighteenth century AD) walled town of 53 ha, surrounded by agricultural farms, within a radius of 2–3 km. It quickly developed after the decay of four previous towns of the area.

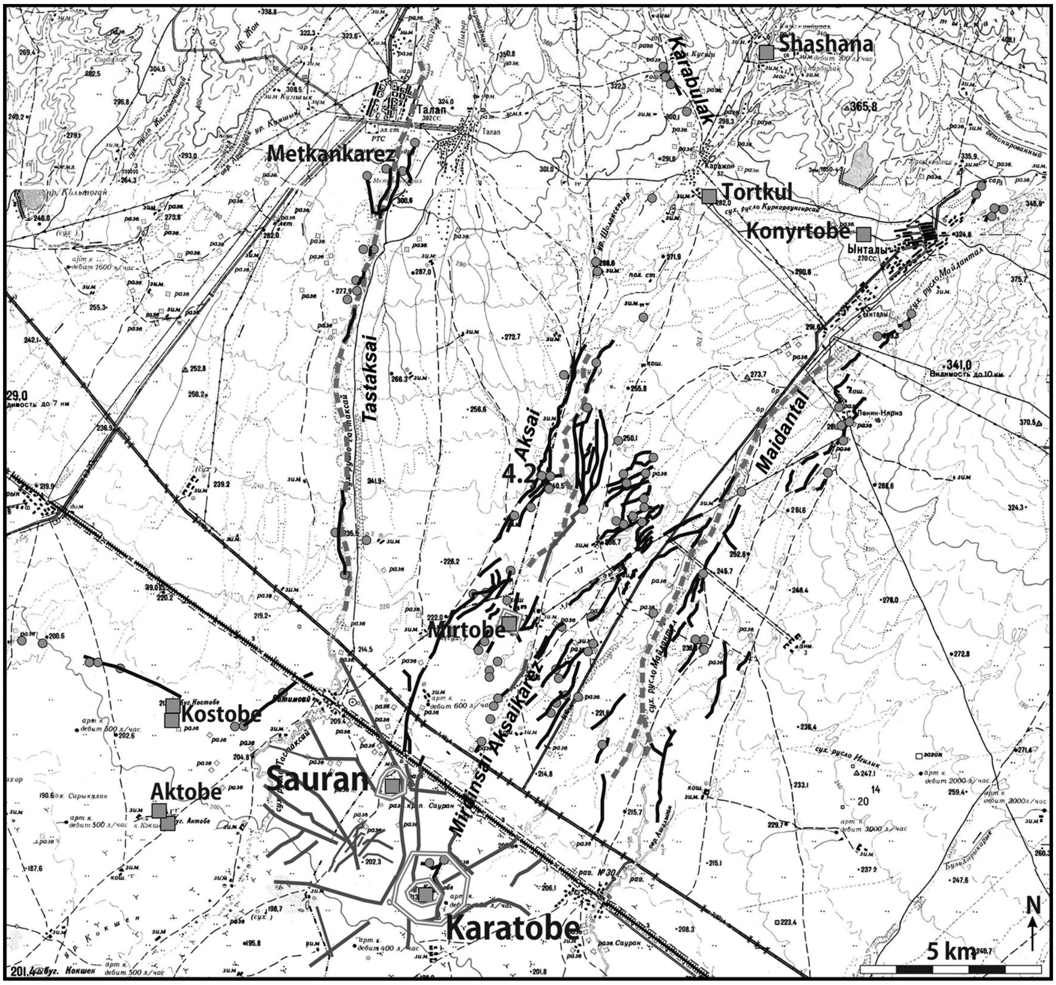

FIGURE 20.7 Map of the karez of the southern slopes of Karatau range (TAM basin, KZ). Black line: karez-GM; gray line: drainage canal; gray dashed line: dry riverbed; gray dot: medieval village; gray square: medieval walled town; gray double line: town walls.

of 471 m, totaling all together 123 km of development, and around 10,000 aligned vertical holes (Figure 20.7) are counted. Most probably, this huge waterwork system evolved gradually in a few centuries, together with the knowledge of the hydrogeological conditions of the area. However, given such knowledge, the entire system could be materially realized in relatively short time and with small labor investment: a brigade of 100 men could dig manually 10,000 wells 3–5 m deep in less than 3 years (Sala 2010). A few campaigns of archaeological works have been dedicated to the study of TAM karez lines, trying to find traces of underground galleries, and have always ended up with negative results, so that the aligned vertical holes are today interpreted as wells of a karez-GM system.

Information about the TAM karez is given by historical sources (Makhmud Zainaddin Wasifi, sixteenth century AD), ethnographic accounts (Dingelshstedt 1889), and reports from three archaeological expeditions (Groshev 1996, pp. 180–189, 2004; Sala and Deom 2005; Sala et alia 2010; Akylbek 2011). Apart from Dingelshstedt, who had the chance to see somewhere a couple of karez with gallery, nobody mentioned or found galleries interconnecting wells.

20.3 SHAFTS OR WELLS? QANAT OR "KAREZ"?

The features and functions of the aquifer SGA (qanat) and of their constituting elements are quite complex and often misunderstood. Generally disregarded are the geomorphological-geological features of the terrain (mountain, foothill, plain, and depression) and of the itinerary of the system, in relation with the type of water source, groundwater circulation, regolith and soil, and so on. Concerning the elements and their functions, the tunnel's functions of water catchment and transport are emphasized, and the processes of water infiltration through the internal walls of tunnels and shafts,* as well as the condensation of atmospheric moisture on them,† are underestimated (Laureano 2012).

Moreover, some of the vertical holes that from the land surface appear as morphologically similar to shafts can instead correspond to something having different structure and function. For example, in the context of aquifer SGA, besides aligned air shafts intended for maintenance and ventilation, sets of vertical holes dug above the start or on the sides of the main line, evidently intended for the artificial recharge of groundwater, are also present.‡ In other words, these holes are not shafts of a tunnel but are drainage and infiltration *wells,* which are intended for catching ephemeral surface water (from seasonal regimes or flash-flood abrupt events or meteoric run-off) and for percolating it underground in order to replenish the aquifer, the mother well, or the tunnel itself. Such wells appear in chaotic clusters (see Figure 20.8) or more or less aligned along the itinerary of a dry hydrographic network that has high infiltration capacity (see Figures 20.9 and 20.10). In this last case, the line of wells would sometimes end above the start of a qanat, but very often, it stands as an isolated and independent scheme, unrelated to any kind of SGA system.

Such lines of wells without underground gallery, in the opinion of the author, constitute the most common case among the aligned vertical holes detected on the land surface of West Central Asia, and represent a most intriguing hydrogeological device that deserves study and interpretation.

First of all, within any artificial groundwater system, two main subsystems and managerial functions must be distinguished: the management of the groundwater source and the management of the water transport to resurgence. In the case of the classic qanat of East Iran, where major groundwater basins are established, the source is a deep confined aquifer, of which the water flow is out of reach of managerial control: a mother well is dug as a water storehouse naturally replenished, and the main task is represented by the tunneled transport of its water for tens of kilometers. However, when such technology is applied to multiple local shallow unconfined aquifers of limited storage capacity, which is the common case in the alluvial fans of the piedmonts of West Central Asia, the aquifer water volumes can and must be previously enhanced through surface-water infiltration and interconnections. And such task, by importance, complexity, and labor investment, becomes equivalent and even superior to the task of transporting and bringing water to emergence at such point that in some regions (such as the Nuratau and Karatau mountains), it represents the characterizing feature of the karez system itself.

The expedients used for implementing the two tasks of aquifer infiltration and of water transport to resurgence are different. The management of the aquifers (replenishment and redirection of their waters) can be done by clusters or alignments of infiltration wells interacting with fossil riverbeds.

* In the Ashrabat region, near the modern Bagyr village, on the west of the Nisa fortress, a qanat line 1 km long and sloping from 369 to 343 m asl presents an anomalous itinerary across a train of four dry riverbeds, witnessing that its gallery plays functions of both infiltration and transport. GPS coordinates: N37°57′38.20″ E58°11′30.78″.

† Condensation of dew and fog, also called "occult" or "horizontal" precipitation, in arid regions represents an important contribution to moisture. It provides daily minuscule quantities but within the year can amount to more than half of vertical precipitation. The condensation on the internal walls of a qanat 1 km long could amount to 600 m^3 per year, that is, to a day of outflow from a weak qanat.

‡ "Sometimes, these supplies are associated with collateral works for the replenishment of water in the soil layers they pass through, such as weirs interred in the riverbed or roadbed torrents and other devices to direct flooding." (Laureano 2012, p. 9)

FIGURE 20.8 Clusters of wells at the start of the qanat line "golan-kariz." Baharden region, northern piedmonts of Kopet-Dag range. GPS coordinates: N38°23′13.04″ E57°22′49.43″. (satellite image, SAS.Planet.)

Water resurgence can be provided in several ways that do not exclude each other, not just by an SGA qanat but also by a terminal simple tunnel without shafts, by a transversal drainage canal, or, in particular geomorphological and hydrogeological locations, even by spontaneous water resurgence out of gravity and/or micro-artesian pressure.

These karez-GM systems, when compared with classic Iranian qanats, are more reduced in scale; they have shorter length, shallower reaches and lesser discharge, but their effectiveness, that is, their specific discharge (L/sec/km), is generally higher and their relative costs are much lower.

We can summarize by saying that in West Central Asia, as soon as we move North and far from the Iranian hydrogeological structure, the artificial management of shallow aquifers becomes more important and the groundwater works develop an unexpected wider and original character, inclusive of two different and equally important subsystems of tasks: for aquifer management (karez-GM) and for terminal water transport to resurgence. We call such systems as GMS, or, in the absence of major confusions and like the local inhabitants, we can keep calling them simply "karez," Central Asia karez, or CA-karez.

Therefore, the question arises, why the presence of such subsystem of aligned infiltration wells in Central Asia does not have been pointed out yet, despite the several studies of aligned ground holes? A possible answer is that the qanat scheme served as the best tentative model for approaching the study of lines of vertical holes and promoted the archaeological search for underground galleries; however, at the same time, it discouraged the perception of other possibilities. Underground galleries have been archaeologically studied in only three of the eight regions spoken above (mainly in the Kopet-dag, and only a few cases in Surkhandarya and Fergana), by the excavation of the final

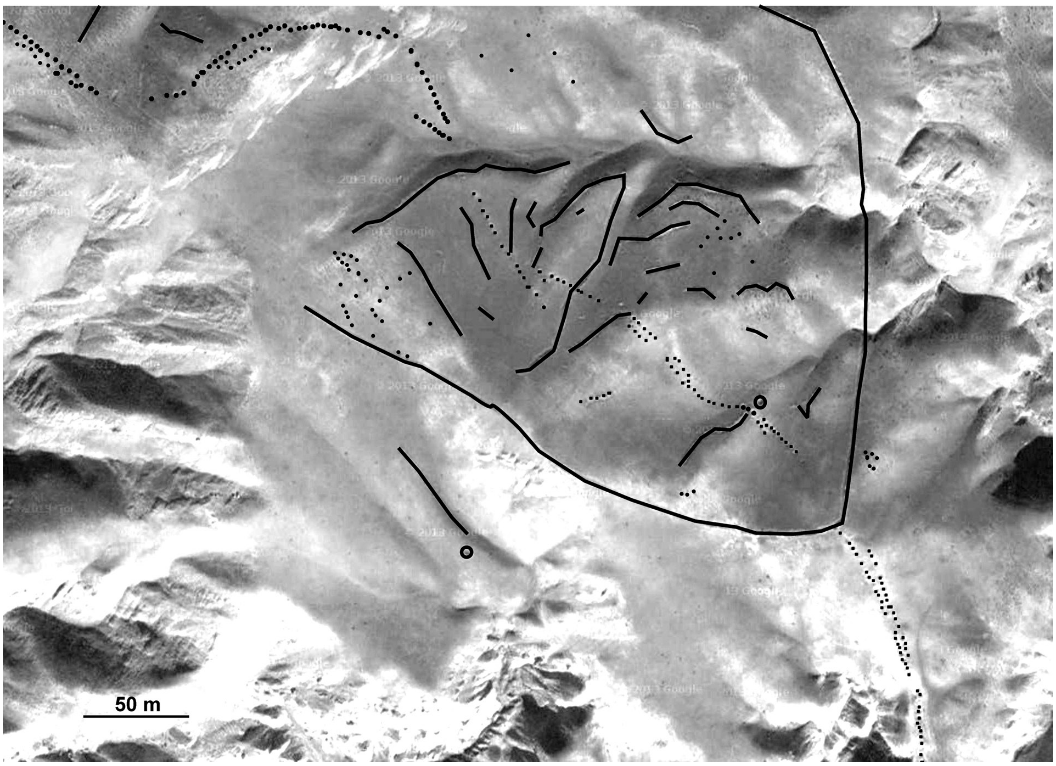

FIGURE 20.9 Karez-like systems in the Djidabulaksai valley at the west of the Kallamazar village (Surkhandarya region). Here, collector channels (black lines) are dug at the bottom of the slopes of the dendritic drainage, and clusters and lines of vertical holes (black dots) are dug in depressions, as if intended for replenishing local shallow unconfined aquifers. The double line of wells continues 0.7 km further south, ending by enhancing a fresh water spring in the surroundings of a farm. GPS coordinates: N37°49′36.04″ E66°59′53.53″. (satellite image, Google Earth 2013.)

segments of the line,* and are just suspected in Central Nuratau, but then, their presence has been extrapolated to all other components of the system, to all the lines of the region, and finally, also to the lines of the other regions.

An example of the persistence of the qanat paradigm beyond its sustainability is provided by the historical accounts and the achaeological reports concerning the karez lines of the TAM region of the Turkestan oasis in Kazakhstan, which are well known to the author. The sixteenth century historian Wasifi quotes the presence of two karez lines but does not give information about their technical aspects (Boldyrev 1957, pp. 167–168). Dingelshstedt, at the end of the nineteenth century, attributes the introduction of the karez technology in the region to the sixteenth century, quotes the presence of 18 karez lines still active, and, after supervising nine of them, found two cases provided with gallery, one of which is in the TAM region (Dingelshtedt 1889, pp. 280–290).

In 1986–1988, the archaeologist Victor Groshev detected two karez lines north of the ruins of the medieval town of Sauran, which interpreted as the ones quoted by the medieval historian Wasifi (see Figure 20.12). According to his report of the 1996, he excavated two wells at the depth of 4 m,† without finding any trace of underground galleries (Groshev 1996, pp. 180–189), but a few years

* The outlet gallery that is normally studied could be just a few hundred meters long tunnel applied as final element of a complex karez-GM system.

† In reality, 11 wells were excavated, 6 of which were dug by bulldozer.

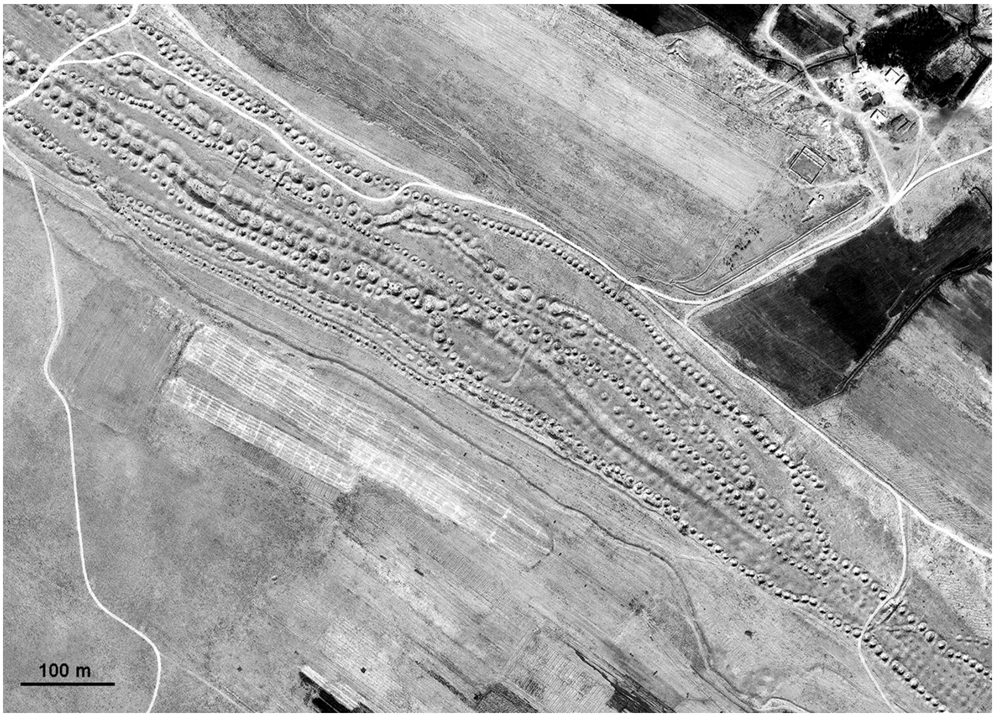

FIGURE 20.10 Band of 12 parallel karez lines dug into the dry bed of the Kalmadjar river, 4 km north of Nurata town (Central Nuratau region, UZ). GPS coordinates: E65°45′02.65″ N40°35′32.65″. (satellite image, SAS.Planet.)

later, in a popular article of the 2004, he quotes the excavation not of two but of three wells to a depth of 6 m and the finding of traces of underground galleries (?!) (Groshev 2004).

In 2002, the Lab of Geoarchaeology of Almaty, besides extensive surface survey and documentation of the entire karez complex of the TAM basin, excavated one well 4 m deep of the same line near Sauran and also analyzed other TAM sites such as the profile of a few karez wells exposed by the erosive floods of the Maidantal river and some collapsed wells that have been enlarged by shepherds for water collection. In each case, no trace of a gallery connecting wells has been found. Moreover, verbal accounts gathered from local aged farmers reported that "there were no galleries, the water was flowing by itself from one well to the other." Further archaeological excavations of two contiguous wells of the same line were implemented in 2011 by the archaeologist Serik Akylbek down to the water table, today at the depth of 12 m, with the same negative result.

20.4 GROUNDWATER MANAGEMENT SYSTEM (GMS)

Simple isolated wells dug into a saturated aquifer are not object of the present article but present few factors that must be underlined in order to understand the functioning of larger systems of clustered and aligned wells:

- The water volume of the well cavity, in the low-porosity silty clay soil of the alluvial fans of arid Central Asia, is 10 times higher than the yield of the water-bearing material of the aquifer.*

* The specific water yield (% of volume) of a saturated aquifer depends on the soil texture: clay holds the 0%–7%, silt and fine sand 10%–28%, sand 20%–35%, and gravel 25%–35%.

- Such kind of low-porosity soil has also low water conductivity,* which would retard the natural recharge of the wellfield.
- Moreover, in the context of such low-porosity soil, a low-permeability layer (aquitard) above a shallow aquifer, supporting its semi-confined character, can be easily formed. In that case, the dig of the well down into the aquifer encounters a differential pressure, favoring a water rise inside the well above the water table (a hydraulic head higher than the water table), that is, a micro-artesian effect.

In the case of clustered wells (wellfield), the total volume of water yield and infiltration is just multiplied correspondently to their number. However, in case the wells are arranged along a sloping line, then three additional factors intervene:

- The differential gravity pressure induced by the sloping gradient will enhance the water infiltration and the micro-artesian effect between wells.
- The wells' alignment favors a privileged itinerary of groundwater circulation, particularly in the case when wells are deep enough to connect overlapping shallow aquifers.
- In case of lines of wells along a fossil riverbed, the groundwater circulation will be strongly enhanced by the presence of horizontal bands of alluvial pebbles. This is also valid for the riverbed itself, which can then represent a potential substitute of artificial wells' lines.

Altogether, the factors spoken above support the idea that systems of clustered or aligned wells could have been used as devices for managing the volume and circulation of groundwater resources, independent of the technique by which such groundwater is finally brought to emergence. Moreover, in the case of aligned wells, under optimal geomorphological and hydrological conditions, these factors also make possible a spontaneous water resurgence at some point along the line itself, which would make of such device an independent system for both groundwater management and water emergence.

20.4.1 Clusters of Wells

Like single wells, sets of wells are relatively common and are located in areas with high water table of shallow unconfined aquifers, clustered on piedmont terraces below steep slopes, aligned along dry riverbeds or transversally between two delta distributaries, and so on. When in small number of 5–10, these wells are just intended for multiplying the water stock that can be uplifted; when numerous, these wells are infiltration wells for replenishing the aquifer.

The last ones deserve special attention. In fact, they are important elements for groundwater replenishment in the context of complex hydrogeological systems made of elements of different kind: clustered wells, lines of aligned wells, and fossil riverbeds for the purpose of groundwater management; and a final pond, an enhanced or spontaneous spring, a qanat SGA, an open drainage canal, and so on for water resurgence.

A simple but impressive example of a system of groundwater replenishment, consisting of just infiltration wells and resurgence ponds, is found in the groundwater basin of the low Kotur-Gyaur river valley at the west of the Kopet-Dag range (TM). This is the most arid desert that from antiquity was crowded with fields and towns, until its total abandonment during Timurid times. Here, during the medieval period, clusters of wells were implemented in takyr depressions in order to subtract

* Hydraulic conductivity depends on soil porosity, saturation, and slope. For vertical movements, clay has conductivity of 10^{-9}–10^{-6} cm/s, silt has 10^{-6}–10^{-4} cm/s, sand has 10^{-4}–10^{-1}, and gravel has 10^{-2}–1 cm/s.

surface floods' water from evaporation, pour it underground, replenish a shallow aquifer, and rise its water table, until water emerges in the lowest relief point as a pond.*

Infiltration wells interacting with a qanat device for replenishing its mother well or its tunnel are found wherever qanats are documented, that is, in most of the alluvial fans of the Kopet-Dag northern piedmonts. For example, on the Baharden alluvial fan, located at the center of the Kopet-dag piedmonts and holding the highest concentration of qanats of the region, clusters of wells are surrounding the start of the qanat lines (Figure 20.8).

More complex systems of groundwater management where clusters of infiltration wells interact with lines of wells and with fossilized remains of dry hydrographic networks are found in all the eight regions (as shown in the below sections).

20.4.2 Aligned Wells

Aligned wells are the most important elements of the karez-GM systems of West Central Asia, not just because they can perform replenishing function but also because they allow to direct the groundwater circulation across overlapping and adjacent aquifers by favoring specific corridors, by using fossil riverbeds, or even by breaking through occasional aquitard zones of low hydraulic conductivity.

Aligned wells are most often built on gently sloping (0.5%–1%) alluvial fans and plains and are parallel to dry riverbeds. Their starting segment is sometimes located in seeping areas or is surrounded by clusters of wells and drainage canals, but most often, it is applied to a dry riverbed (Figure 20.9). Their course is sometimes represented by a single line but most often by few parallel lines or even by bands of lines inside a dry riverbed (Figure 20.10). Their terminal segment is most often ending in the same dry riverbed or in a neighbor riverbed or is finally releasing water as an enhanced spring or into a short tunnel or in a drainage canal.

Complex systems of aligned wells are most widespread in the Surkhandarya, Nuratau, and Karatau regions, where the groundwater management of the aquifer has been developed at such point that the water transport, and, in some cases, even the water resurgence, can happen without the help of underground galleries. A deep knowledge of hydrogeological principles must be suspected by part of the building masters of such marvelous and sustainable implementations.

The principle underlying these schemes is that a number of shallow overlapping aquifers distributed at different elevation on the sloping alluvial plain must be recharged by clustered and aligned wells and must be wisely interlinked by wells' lines and fossil riverbeds. In that way, enhanced volumes of groundwater will circulate, from aquifer to aquifer, until enriching a final water-bearing soil, where resurgence waterworks are applied. Under favorable geomorphological, hydrological, and climatic conditions, a very high water table will be established somewhere along the way, favoring the spontaneous water resurgence, by gravity and micro-artesian pressure, from an enhanced spring or from the last wells of a line† (Figure 20.11).

Small canals are often paralleling the last segment of such lines, directed to small fields and villages located in proximity of these spontaneous water resurgence points; large agricultural areas and towns are built at the terminal water outlet of the system.

* In subsequent soviet times, the entire Messerian plain has been covered by a regular lattice of lines 40–50 km long in the SN and WE directions, intersecting each other every 1–2 km, made of wells 100 m far from each other. They are clearly visible on satellite images, looking as a gigantic waterwork. Instead, they represent geological drills for hydrocarbons research.

† The articles of R. Sala on the subject of karez show successive steps of understanding. At the beginning (Sala 2003), the author is still showing some confidence in the existence of classic shaft-and-gallery systems. Then, in the following articles, after the absence of galleries was finally proved, the spontaneous water resurgence along the lines of wells is suspected and mainly attributed to a micro-artesian effect. Finally, in the present article, the geomorphological conditions of the terrain and the distribution of shallow aquifers are pointed out as precondition for the realization, by aligned wells and fossil riverbeds, of a complex Groundwater Management System (GMS), from which the water outflow can be provided in different (and complementary) ways: by an SGA, a drainage canal, or spontaneous resurgence out of gravity and micro-artesian pressure.

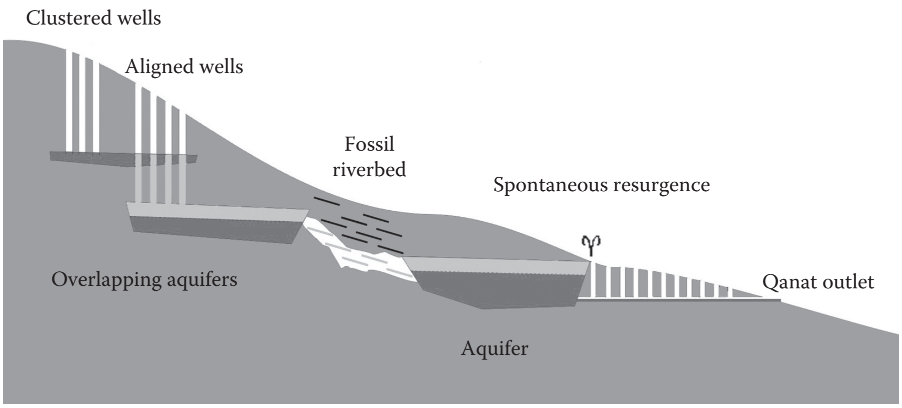

FIGURE 20.11 General scheme of a Groundwater Management System (karez-GM, GMS). Clustered wells replenish the aquifer; aligned wells and fossil riverbeds interconnect aquifer lenses at different elevations. Water resurgence can happen spontaneously or by shafts-and-gallery transport (qanat). (Courtesy of R. Sala.)

20.4.3 The GMS of the Turkestan Oasis

The TAM region displays a majestic case of groundwater management, concerning an area of 20×20 km^2. The seasonal streams of Tastaksai in the West and Maidantal in the East, as soon as they leave the mountain zone, start converging the respective groundwaters in a depression located between them, where the fossil riverbeds of the almost inexistent Aksai stream are detectable. This convergence point represents the upper start of the TAM GMS, the main objective of which is to provide water 20 km south, 60 m asl lower, to the medieval agricultural fields and town of Sauran (Sala and Deom 2005; Sala et alia 2010; Figure 20.7).

The provision of water to the Sauran plain does not happen by direct water flow but through the complex alternation of wells' lines (karez lines) and paleo riverbeds, which replenish and put in connection discontinuous shallow aquifers located at different elevations. Two main GMS karez systems of groundwater circulation are established on the right and left banks of the Aksai riverbed: the right way is fed by the Tastaksai groundwaters, while the left way is fed by the Maindaltal's groundwaters. Only two lines of wells at the end of the right bank scheme (the lines that have been object of archaeological excavations) reach finally the northern borders of the Sauran town (Figure 20.12); the other wells' lines and the final groundwater stock as a whole are caught by two open-drainage canals (5–6 km long) converging to the town from the final delta distributaries of the Tastaksai river on the West and the Maidantal on the East.

Several points of probable spontaneous water resurgence are detected along the way, starting from wells along the course of particular karez lines. In fact, in 50% of the cases, the middle and lower segments of the karez lines are paralleled by a canal, and the corresponding wells have an inclined mouth's plane, as if intended for discharging groundwater into it.

In proximity of these points, traces of ancient fields and the ruins of more than 100 medieval farms are found. At the very center of the left bank system, 5.5 km north of Sauran, the ruins of a rectangular walled town of 19 ha, Mirtobe, are standing. They subsisted during four centuries (fourteenth to seventeenth century AD) in a desert landscape totally fed by resurgent karez waters.*

* GPS coordinates of Mirtobe: N43°33'28.69" E67°48'29.73".

FIGURE 20.12 Aerial photo of karez line developing until the northern periphery of the medieval town of Sauran (thirteenth to eighteenth century AD). View to SE. GPS coordinates of the first well at the bottom left corner of the photo: N43°32′04.37″ E67°46′28.80″. (Courtesy of R. Sala).

This corresponds to the "*charbag*" (quadrilateral garden)* that Wasifi quotes as built on one of the Sauran karez lines, "similar to nothing that people traveling all around the world had ever seen neither on land neither on sea" (Boldyrev 1957, pp. 167–168).

20.5 CONCLUSIONS

Underground waterworks and, in particular, groundwater mining structures have been essential tools for the medieval colonization of the most arid expanses of West Central Asia. A few different types can be distinguished on the basis of the kind of water source and the technique of its transport to emergence: surface SGA (tunnels), aquifer SGA (qanat), karez-GM.

Both the last two structures are applied to groundwater sources but differ by function and technology: qanats are mainly planned for groundwater catchment and transport through galleries with shafts, whereas karez-GM are mainly devoted to management (replenishment and redirection) of groundwater circulation by lines of infiltration wells. The two types are potentially independent but not incompatible structures and can interact complementarily in the context of a complex system (GMS).

The SGA waterworks have clearly an Iranian origin, whereas karez-GM seem to be the result of an original West Central Asian development adapted to hydrogeological contexts made of multiple shallow overlapping aquifers.

The karez-GM are by far the most widespread type of waterworks in West Central Asia, which is explained by the fact that, given a preliminary sound knowledge of groundwater circulation, they represent an easy, quick, cheap, and most sustainable way of groundwater mining. Despite these highly profitable features, in the last 100 years, they have been substituted by the hydraulic schemes

* "This highly structured geometrical scheme, called the 'chahar bagh,' became a powerful metaphor for the organization and domestication of the landscape, itself a symbol of political territory" (Fairchild Ruggles 2008). The Islamic "charbag" are inheritors of the Old Persian tradition of paradise (in Persian meaning "walled": pairi = around, diz = walls) gardens, always built in arid landscapes.

introduced by the Russian and Soviet colonizations (dams, canals, pipelines, electric pumps), and finally their technology has been totally forgotten.

The rediscovery of this obliterated technique represents a rare contribution by part of the archaeological discipline to the geological sciences, that is, to the hydrogeological and hydro-engineering disciplines; and its renewed implementation could have worldwide economic significance for modern water mining and land reclamation in arid zones.

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