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Qanats: Ancient Innovations Nurturing Sustainable Futures in Water Management

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Abstract
The qanat, a timeless testament to human ingenuity, emerged on the arid Persian Plateau around three millennia ago as a sustainable solution to water scarcity. This technique channels water from aquifers using gravity through gently sloping sub-horizontal tunnels, avoiding over-extraction and ensuring a delicate balance between human needs and environmental preservation. By naturally regulating water flow according to aquifer levels, qanats prevent excessive depletion, serving as a model for sustainable water resource management. This study explores the fascinating journey of qanats, their geographical spread, historical evolution and enduring relevance. We highlight their adaptability to diverse environments, their role in fostering cultural continuity and their potential to address contemporary water challenges. By revisiting this ancient marvel, we uncover valuable lessons for contemporary water management systems worldwide.

KEYWORDS
Oases
Qanats
Groundwater
Resource management
Ancient hydro-technologies

WATER ICONS

Policy Recommendations

- Enhancing and safeguarding the heritage of qanats in their various territorial forms by preserving not only their historical legacy but also their functionality and efficiency as integral components of an integrated water management system.
- Prioritizing groundwater extraction through technologies like qanats, which operate without energy use and prevent aquifer depletion, ensuring sustainability and long-term functionality of water resources.
- Promoting the tangible and intangible heritage of qanats as a catalyst for dialogue and cultural and political exchange in addressing future challenges.
- Revitalizing and strengthening administrative and democratic bodies to supervise regions where qanats are present, ensuring a shared vision beyond individual interests.

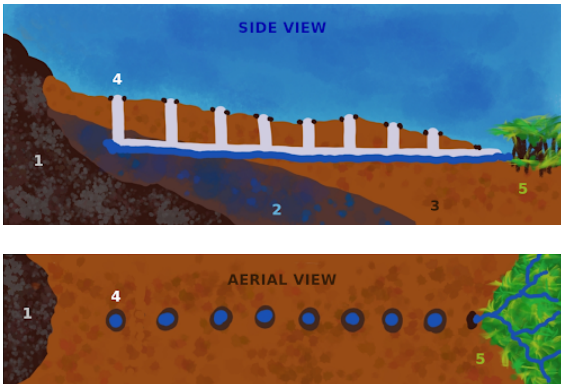
< Fig.1 Qanats of Bam (Source: S.H. Rashedi, 2014. Nomination File, © S.H. Rashedi, whc.unesco.org/en/documents/141554).

Introduction

Qanats, a cornerstone of traditional irrigation systems, exemplify a profound understanding of the harmonious relationship among humans, technology and nature. Originating on the arid Persian Plateau approximately 3,000 years ago, qanats addressed the challenge of water scarcity in arid around semi-arid regions (Barontini et al. 2018; English 1968; Lightfoot 2000, 2024; Remington 2018). These systems consist of gently sloping underground tunnels that transport groundwater from aquifers to surface areas using gravity alone. Qanats operate passively, delivering water sustainably. When aquifer levels are high, qanats yield more water, while during droughts, their output naturally decreases, preventing over-extraction and preserving long-term aquifer health. This self-regulating mechanism aligns qanats with natural groundwater cycles, supporting human activities such as drinking water supply, agriculture and horticulture. The ingenious design of qanats minimizes evaporation losses, allowing water to be transported over long distances in harsh climates. This sustainable approach has endured the test of time, inspiring numerous adaptations in diverse regions (Ashraf et al. 2016; Barontini et al. 2018; Barontini et al. 2017; Chunliang et al. 2014; Himat and Dogan 2019; Khan and Nawaz 1995; Martínez-Medina et al. 2018). This study examines the evolution and diffusion of qanats, tracing their development in ancient Persia and global spread, while emphasizing their contemporary significance in sustainable water management.

Historical and Geographical Diffusion of Qanats

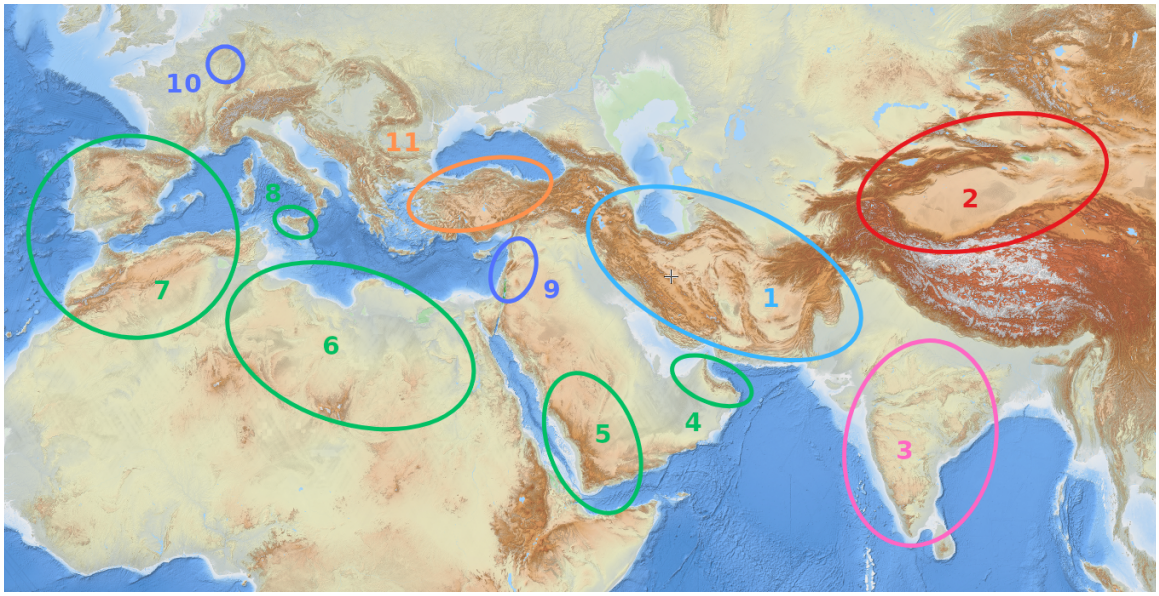
The qanat system, originating in the heart of the Iranian Plateau along the internal fringes of the Zagros Mountains, likely emerged during



^ Fig. 2 Scheme of a qanat section: 1 Bedrock; 2 Water table, saturated zone; 3 Alluvium, unsaturated dry zone; 4 Mother well; 5 Outlet. The qanat drains water from the water table (Source: Massimiliano Borroni, 2024).

the early first millennium BCE as an innovative response to arid conditions and the scarcity of stable, high-quality surface water. The period before the advent of qanats saw advancements in metalworking, which in turn drove progress in mining technologies. Early Persian farmers and miners, noticing water seepage in mining tunnels, adapted this knowledge to channel groundwater for irrigation. By connecting aquifers to farmland through gently sloping tunnels, they developed a reliable and sustainable irrigation system.

The rise of the Achaemenid Empire (550–330 BCE) coincided with the early diffusion of qanats. Ancient sources link the establishment of this imperial power to the extensive use of cavalry, which required substantial agricultural surpluses to sustain the animals. The dissemination of qanat technology made it possible to cultivate arid plains and expand agricultural areas, generating the surpluses needed to support the cavalry. Recognizing the strategic value of this innovation, the Achaemenids actively promoted the spread of qanats, creating a positive feedback loop that reinforced agricultural productivity and military strength (English 1968; Massoud 2022).



^ Fig. 3 Diffusion of qanats: 1 Iranian Plateau, place of origin; 2 Xinjiang region; 3 Deccan Plateau; 4 and 5 Oman, Yemen and Saudi Arabia; 6 Egypt and Libya; 7 Algeria, Morocco and Iberian Peninsula; 8 Sicily; 9 Syria, Jordan and Palestine; 10 Luxembourg; 11 Anatolian Plateau and Greece (Source: Vladimiro Andrea Boselli, 2024).

In summary, the agricultural surpluses generated by this ingenious irrigation system were instrumental in the empire's rise, supporting the development of a formidable cavalry that became a cornerstone of its military power. However, two centuries later, Alexander the Great's introduction of the Macedonian phalanx rendered cavalry tactics ineffective. This shift in military strategy contributed to the empire's downfall, culminating in Darius III's assassination by his own generals following their defeat in Bactria in July 330 BCE.

Persian rulers incentivized qanat construction by granting builders land and water rights for multiple generations, leading to the widespread adoption of this technology across their vast empire. Qanats initially spread westward to Mesopotamia, the Levant and Egypt, and eastward to Afghanistan, Central Asia and the Turpan Basin in western China (present-day Xinjiang) (Chunliang et al. 2014; English 1968; Lightfoot 2024; Massoud 2022). Administrative oversight during imperial expansions further facilitated the dissemination of this ancient system. The system was adapted to suit the specific environmental, hydrogeological and cultural contexts of various regions, reflecting the technique's intrinsic flexibility.

During the Roman-Byzantine period (64 BCE–660 CE), qanats were introduced to parts of Europe, including the Iberian Peninsula and the region of present-day Luxembourg. In the Levant, encompassing Syria, Palestine and Jordan, qanats were integrated into Roman aqueduct systems. However, during this period, Roman aqueducts remained the dominant form of water infrastructure. In Roman Gaul, qanats extended as far as present-day Luxembourg, where the Raschpëtzer qanat, dating to around 150 CE, operated for approximately 120 years (Govindan Kutty 2020; Kayser and Waringo 2000).

A second major wave of qanat diffusion occurred during the rise of the Islamic caliphates in the seventh century and beyond. This expansion brought qanat technology to coastal areas of North Africa, the Iberian Peninsula and Sicily. During this period, the deepening of hydraulic knowledge over the first five centuries of the Islamic era led to significant advancements in qanat construction and maintenance techniques. With the establishment of Islamic sultanates in northern India (eleventh–thirteenth centuries) and later in the central Indian subcontinent (fifteenth–eighteenth centuries), qanat technology spread across the Deccan Plateau (Barontini 2017; Govindan Kutty 2020). The diffusion of qanats during the Islamic period is well-documented, highlighting the existence of skilled labor teams, with each member specializing in a specific aspect of construction or maintenance. These teams, benefiting from the hydraulic knowledge accumulated during the early Islamic era and equipped with technical manuals in Arabic and Persian, further refined qanat technology (English 1968; Lightfoot 2000; Madani 2022; Malik et al. 2021; Martínez-Medina et al. 2018; Remington 2018). They likely facilitated the spread of qanats along trade routes connecting Central Asia and North Africa, particularly in regions with high demand for sustainable irrigation systems. These trade routes often strengthened oasis centers, enabling the expansion of irrigated agriculture and reliable water supplies in arid regions (Madani 2022; Massoud 2022; Messous 2024; Strava 2024). Later, Spanish colonists, familiar with qanat systems from their homeland, introduced variants of the technology to Latin America. They established qanats in regions such as Mexico, further extending the global legacy of this ancient innovation and enriching similar Indigenous pre-Columbian techniques, such as the *puquios* of Peru and northern Chile (Barontini et al. 2018; English 1968; Martínez-Medina et al.).

Localization, Adaptation and Regional Names

The diffusion of qanats followed ancient trade routes and the expansion of empires. This fact allows us to highlight the deep connection between centralized administration and qanat construction. The building and maintenance of qanats, like Roman aqueducts, could be managed by tightly organized local communities without extensive centralized authority, like oasis communities, or by labor groups directed and financed by central authorities or owners of large amounts of land. After the construction of a qanat, the relatively simple maintenance required was often left to the population occupying the area it served to irrigate. This was unlike the great architectural structures of Roman aqueducts, which required highly skilled and specialized workers for upkeep and resulted in the conservation of many functional qanats and the progressive abandonment of the big Roman aqueducts. This can also be observed in oasis regions of North Africa, the Persian Plateau, and the Deccan Plateau of India, where local communities maintain and modernize qanat networks (Ashraf et al. 2016; Govindan Kutty 2020; Himat and Dogan 2019; Khan and Nawaz 1995; Malik et al. 2021; Massoud 2022; Messous 2024; Taghavi-Jeloudar et al. 2013; Weingartner 2007).

Local conditions and cultural influences shaped unique adaptations and regional names, reflecting the integration of qanat techniques into local knowledge systems (the variety of languages involved leads us to abandon any claim to uniformity in romanization). While the word *qanat* is common in the Arabic speaking world (e.g., Iraq and Syria), in Sicily they are called *canate arabe* ("Arab qanats"). In Northern Iraq, Central Asia and parts of India, the Iranian word *karez* is commonly used (sometimes transcribed as *kareez* or *kariz*), and in India we

find terms such as *kharejari*, *surang-bawdi, surangam, nahar* and *kundi bhandara*. In China's Xinjiang region, the system is known as *kanjing* or *kanerjing*, or again *karez*. The *dawudi falaj* (pl. *aflaj*) is another name for these underground tunnels, a term that we find in Oman and Saudi Arabia. In Southern Jordan, the name *dhwawi* may be used. In North Africa, specifically in Libya and Algeria, the system is known as *foggara*, and in Morocco, as *khettara*. In the Iberian Peninsula these systems are known as *galerías* ("tunnels"), a term carried to Mesoamerica and South America during the Spanish conquest (Barontini et al. 2018; English 1968; Martínez-Medina et al. 2018).

Contemporary Relevance and Future Sustainability

Qanats transcend mere technological innovation: they embody cultural and ecological heritage. Their construction and maintenance required communal effort, fostering collaboration and governance practices. Rituals and traditions surrounding water distribution underscore their central role in desert communities' social and spiritual lives, creating a shared sense of responsibility toward water as a precious resource.

In Spain, the *galerías con lumbreras* system in the southeastern region provides a striking example of qanat-inspired adaptation to address local challenges. One notable example is the Caño-Contracaño in Murcia, a qanat-like system designed to manage water efficiently. Beyond irrigation, it plays a vital role in mitigating eutrophication in saline lagoons, demonstrating how traditional techniques can be repurposed for modern environmental management strategies. The Caño-Contracaño's use of interconnected channels and ventilation shafts exemplifies the adaptability of qanat systems to local hydrological and ecological conditions. This harmonious blend of old and new highlights how heritage preservation can coexist with contemporary utility to create sustainable resource management frameworks (Martínez-Medina et al. 2018).

Oman offers another inspiring case of qanat revitalization. In the 1980s, government-led initiatives restored *aflaj* systems, ensuring the preservation of traditional practices while enhancing water accessibility. This effort underscores the potential of qanats to bridge the gap between heritage conservation and practical resource management, particularly in arid regions where water scarcity is a pressing issue (Remington 2018).

Similarly, the Naubad Karez in Bidar, India, has recently undergone conservation efforts, illustrating the ongoing relevance of qanats as decentralized water sources. These ancient systems offer viable solutions for sustainable urban and rural water supply, especially in areas grappling with dwindling aquifers and the adverse effects of over-extraction (Govindan Kutty 2020).

These contemporary applications highlight the enduring relevance of qanats, demonstrating how ancient wisdom can inspire innovative solutions for modern water challenges. Beyond their practical applications, qanats hold untapped potential as cultural and ecological tourism assets. Their unique design and historical significance captivate the imagination, transforming them into compelling attractions that celebrate human ingenuity in water management. From Spain to Oman, Iran, India and beyond, qanats can serve as focal points for heritage tourism, fostering economic opportunities while raising awareness about sustaina-

^ Fig. 4 Example of recent maintenance of a khettara near Ait Zeggane (Morocco) with modern techniques and materials. On the left, the systems for moving the material along the wells; in the center, two wells renovated with stone and bricks respectively; on the right, the maintenance work, during and after, in a slightly kilned well (Source: Mhammad Houssni, 2024).

ble water practices. By seamlessly integrating traditional knowledge with modern needs, qanats stand as enduring symbols of resilience and innovation. Their lessons, deeply rooted in harmony with natural resources, offer a timeless blueprint for the sustainable development of water systems worldwide (Barontini et al. 2018, 2017; Massoud 2022; Messous 2024; Taghavi-Jeloudar et al. 2013; Weingartner 2007).

Conclusion

The historical evolution and geographical diffusion of qanats underscore their enduring significance. By bridging diverse cultures and enabling sustainable resource management, qanats exemplify the potential of traditional knowledge to address modern challenges. Reviving this heritage not only honors its cultural legacy but also inspires innovative approach-

es to water resource management, blending ancient techniques with modern technology. This fusion can help mitigate issues such as groundwater depletion and inefficient irrigation practices. Moreover, it encourages global cooperation in water management, fostering knowledge exchange and intercultural collaboration to combat the growing threat of water scarcity worldwide.

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