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The technology, management, and culture of water in ancient Iran from prehistoric times to the Islamic Golden Age

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Despite Iran's longstanding reputation for sustainable water management, the country currently faces mounting water-related challenges caused by population growth, industrial development, urban sprawl, lifestyle changes, climate change, territorial conflicts, poor management, and insufficient public participation. Since past and present water-related challenges share similar origins and patterns, addressing the past is imperative. After gathering, contextualizing, verifying, clustering, coding, and corroborating sources, we conducted a historical study to examine the relationship between water and Iranians from prehistoric times to the Islamic Golden Age (1219 AD). According to the findings, in prehistoric Iran, drought, flooding, river course changes, and the absence of a central government severely impacted water development. Despite doubts about the qanat's origin, archaeological investigations indicate in the proto-historical period, qanat systems existed in Iran and the Arabian Peninsula. In 550 BC, the Achaemenids initiated a fundamental transformation in Iran's water history by building dams, qanats, and water canals under a centralized administration. After a slump during the Seleucids (312–63 BC) and the Parthians (247 BC–224 AD), Iranians practiced water governance reborn under the Sassanids (224–651 AD). The Sassanids, like the Achaemenids, formed a powerful statement of unity, cooperation, and support among people for implementing their major water-related plans after enhancing institutions, laws, and communications. Chaotic Iran, however, endured severe water-related weaknesses in the Late Sassanids. Throughout the Islamic Golden Age, Iranians successfully traded water knowledge with other nations. As seen today in Iran, the Iranians have been unable to thrive on their resources since the Mongol invasion due to weak water governance, political tensions, and poor public support. The water sectors face more severe challenges when ancient water systems are ignored, applied without enhancement, or blindly adopted from other nations. Therefore, before current problems worsen, it is essential to integrate traditional and modern water cultures, technology, and management techniques.

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Introduction

Water is fundamental to life and health, food security, economic expansion, social development, political stability, and ecosystem preservation. It has always formed and transformed societies, economic structures, demographic dynamics, political systems, and cultural makeup, causing harmony or tension. Humans, in turn, have actively managed, governed, and ultimately developed water resources by implementing structural and non-structural measures and a set of rules, practices, and processes. The development of water resources has always occurred concurrently with societal development, and both actions have been influenced by time, geography, and climate.

Due to Iran's geographical location, climate variations, and unequal distribution of water resources, developing water resources has always been challenging, intertwined with various natural and anthropogenic factors. Over millenniums, Iranians have practiced different strategies to rationally link between water availability (surface water and groundwater), spatiotemporal requirements, geoclimatic conditions, cultural values, legal rights, technological tools, political power, and socioeconomic privileges. Today's Iran, however, faces significant challenges in managing its water resources, some of which are rooted in the past. In this regard, an understanding of water-society systems in the past can assist us in forming the present, as well as shaping the future.

This research explores water's geographical, cultural, technological, and governance domains and their relations with human society from prehistoric times to the Mongol conquest of the Khwarazmian Empire. This study aims [i] to discuss the evolving relationship, which exist between man and water during prehistoric and historical periods; [ii] to gain a better understanding of the interaction the government, politics, security, economy, science, technology, and culture on the one hand and the development of water resources on the other hand; [iii] to determine the critical reasons for past failures and successes in developing water and apply them to present-day problems.

It is a common problem for researchers and policy-makers to lack adequate knowledge about Iran's water history. Despite improved access to and sharing of data, Iranian researchers are less interested in water history than other water-related subjects. Iran's situation becomes more acute when the overwhelming majority of the Iranian population does not believe that past solutions can be applied to contemporary problems. Consequently, in present-day Iran, the traditional water-related technologies, tools, problem-solving abilities, positions, cultures, traditional costumes, beliefs, and rights are disappearing at the same rate as they are replacing by non-natives. In this context, by reconstructing and updating past achievements, we come up with better solutions to current and future water-related concerns.

Several historical investigations have examined various aspects of hydrology and hydrogeology of ancient Iran (Kuros and Labbaf Khaneiki, 2007; Gholikandi et al., 2013; Manuel et al., 2018; Rigot et al., 2021). The majority of these studies deal with [i] water infrastructures such as weirs, dams, qanats, watermills, [ii] water resources governance, [iii] socioeconomic facets of water, and [iv] architectural design of water-related systems. Throughout this research, fascinating glimpses into Iranian water governance, technology, culture, and knowledge are provided to better understand history. We attempted to cover all of the above topics throughout the research process. To the best of our knowledge, previous studies of this kind have not adequately dealt with this topic (i.e., covering a broad spectrum of the thematology in a particular period). Although it is impossible to cover all areas of this topic in one article, this one tries to cover some of the basics.

Methods

After defining the research topic and its objectives, data collection was preceded by searching for desired terms, alternative terms, and combinations of terms determined based on the research scope, the author's background information, and similar studies' keywords. Several search engines were used to locate the selected terms, including Science Direct, Taylor & Francis, Springer, Scopus, Google Books, and Google Scholar for international documents, as well as Iranian Scientific Information Database (SID), IranDoc, Civilica, Normgaz, and MagIran for national documents. The search procedure was repeated several times to obtain new sources. In total, 460 documents were reviewed for credibility and content, and 242 were grouped based on the topics and period they covered[1]. Afterward, comparative historical research is conducted to determine the status of the water from prehistoric times until the end of the Islamic Golden Age (i.e., the end of the Khwarazmian rule). This period was chosen for the research because, in three critical moments during this time (i.e., the Achaemenid, Sassanid, and Islamic eras), Iran experienced significant changes in management, technology, development, and water culture. In the next step, historical sources were summarized and consolidated. Our final stage consisted of interpreting the water-related events and their relationship to conclude.

The knowledge of the history of water in Iran is founded mainly on archaeological traces, residues, and remains (texts, tablets, artifacts, material culture), and other ethnographic observations (original or translated) from different historical periods. However, in a politically turbulent and geo-climatically heterogeneous country like Iran, cultural heritages, historical documents, and archeological records are susceptible to gradual or instantaneous deterioration from natural factors (e.g., weathering, flooding, storms, earthquakes, temperature differences, rockfall, and landslide) and human destructive factors (e.g., improper site management, developmental disturbances, land-use change, illegal excavations, military activities, burning of libraries and archives, political tensions, and suppression of ethnic and religious beliefs). In a logical process, a past event has to be witnessed, then the observations recorded, the record preserved for varying periods of time, then found, and finally understood. A lot of historical evidence, therefore "cannot really ever become available, but such silence cannot be used to justify the conclusion that the absence of evidence is evidence of absence. In many cases, archaeological and historical materials have not been thoroughly studied or dated with high confidence. For instance, many ancient clay tablets and administrative records remain intact due to political and scientific reasons. Persepolis Fortification Tablets, dated back to 492–457 BC in the reign of Darius the Great, are characteristic examples of the Achaemenid records, most of which have not been translated (Root, 1997). Of the ~30,000 clay tablets (10,000 intact pieces, 10,000 more or less complete ones, and probably more than 10,000 fragments), 2100 texts were transcribed, interpreted, and published (Jones and Stolper, 2008). While Iranians have been writing history since the Achaemenid period, most historical resources, especially those of pre-Islamic times, were authored by non-native historians. Their lack of familiarity with Iranian customs and culture might affect portraying Iran's past. Consequently, in some cases, the lack of information, which improved our knowledge of water conditions in the past, is evident.

Study area description. With an area of 1,648,195 km^2, Iran[2] lies between 44° 02′ E and 63° 20′ E longitude and 25° 03′ N to 39° 46′ N latitude[3]. It stretches from [i] the north to Azerbaijan,

Fig. 1 Map of Iran showing the provinces. By size and population, Iran is ranked 17th and 18th in the world. Approximately three-fourths of Iran's population resides in urban areas, mostly in water-rich regions of northwestern, western, and northern Iran. Out of 31 provinces, Kerman and Sistan and Baluchestan are the driest, while Gilan and Mazandaran are the wettest. Khuzestan and Ardebil have the highest and lowest temperatures, respectively.

Armenia, Turkmenistan, and the Caspian Sea, [ii] the east to Pakistan and Afghanistan, [iii] the south to the Persian Gulf and the Sea of Oman, and [iv] the west to Turkey and Iraq (Fig. 1). Nearly a third of the country's 8334 km border is a water border. Iran is mountainous and rough, covered by the Northern Alborz and Western Zagros Mountain ranges (Jamali, 2021). In general, the country's soil is not suitable for large-scale agriculture. In Iran, 11.2% of the land is cultivated (Ehlers, 2021). Salt sterile desert (19.7%), natural pastures/rangelands (48.1), forests (8.7%), industrial/residential areas (7.3%), and water bodies (5%) surround the remnant (Mousavi et al., 2020).

Iran has a wide variety of climatic conditions. Climate variability arises from the region's size, type of air masses that enter, geographical latitude, topographical altitude, and land position to water bodies. Iran's different types of climate include hyper-arid regions (~35.5% of the total area) in the central and southeastern parts, arid regions (~29.2%), and semi-arid regions (~20.1%) in the southern, eastern, and northeastern parts, Mediterranean climate (~5%) in the west, and humid to hyper-humid regions (~10.2%) on the southern coast of the Caspian Sea (Amiri and Eslamian, 2010). The average annual temperature (1973–2018) is 17.6 °C (Economics, 2019). The total annual rainfall is averaged at 228 mm (a fourth of the world's average)[4], with ~50% falling in winter (corresponding to the minimum water demand), ~23% in spring, ~23% in autumn, and ~4% in summer (corresponding to the maximum water demand) (Economics, 2019). To justify the temporal distribution of precipitation, it is necessary to describe the effective air masses in the country. In the hot seasons, subtropical high-pressure air masses[5] influence Iran, whereas, in the cold seasons, low-pressure air masses develop in the Mediterranean Sea[6] and Sudan[7]. Moreover, South Asian monsoon air masses enter the country from the Indian Ocean and the Sea of Oman, affecting a small southeastern part of the country in the summer. For these reasons, Iran generally enjoys cold/wet and hot/dry climates in winter and summer, respectively (Zarrin and Dadashi-Roudbari, 2021). Such conditions can be exacerbated by high-altitude differences between the plains and mountainous regions. From a geographical view, overall, the precipitation ranges from less than ~20 mm/yr in the southeast, east, and central parts to more than ~1000 mm/yr on the southern coasts of the Caspian Sea (Mousavi, 2005). Another significant spatiotemporal factor in water availability is evaporation. The annual average evaporation ranges between 1,500 and 2,000 mm, nearly three times the global average. A large quantity of the annual rainfall (~70%) rather than being used or percolated (IPBO, 2020). The rainfall shortage and a high evaporation rate are the primary reason for low water circulation. One of the consequences is that rivers in Iran are primarily ephemeral with small discharges and have not been distributed regularly.

Water's significance in prehistoric Iran. The Iranian Plateau was home to early modern humans who dispersed from Africa between 90,000 and 50,000 years ago during the Middle-Paleolithic of the Stone Age (Delson, 2019). The oldest-known artifacts from the Middle-Paleolithic, such as stone tools, have been discovered at [i] the Varvasi Cave in the Dinurab River Basin[8], [ii] Yafteh Cave in the Khorramabad River Valley[9], [iii] Kashaf-rud[10] site along the Kashaf-rud River Basin[11], and [iv] Ganj Par site around the Sefid-rud River[12], signifying the human existence in water-rich regions of western and north of Iran (Vigne et al., 2005). In the 6th and 5th Millenniums BC, the earliest sparse and dispersed villages (e.g., Tape Chahar Boneh[13], Chogha Bonut[14], Ali Kosh[15], Ganj Dareh[16], Tape[17] Pardis[18], Cheshmeh Ali[19], Tape Sialk[20] North, Period I, Tape Zaghah[21], and Tape Sarab[22]) emerged in southwestern, western, and northwestern Iran, where perennial water bodies, rainfall, and fertile alluvial soils allowed agrarian societies to flourish (Alizadeh, 2003; Hole, 2004; Zeder and Hesse, 2000). In the meantime, the earliest domestication of animals began in the Taurus and Zagros Mountains[23] (Farzadmehr and Nazari Samani, 2009; Riehl et al., 2013). Nomadic pastoralism was practiced in southwest Iran in the early stages of domestication (Helmer et al., 2005; Zeder, 2008; Gallego-Llorente et al., 2016). The beginning of irrigation agriculture in Iran is dated to 5220–4990 BC (Farzadmehr and Nazari Samani, 2009). Irrigation management was potentially organized on the level of family or kinship groups, focused on simply breaching the levee of natural watercourses. Due to the arid to semi-arid climate conditions, crop cultivation in prehistoric Iran had been heavily focused on rain-fed winter crops, sowing in October/November, and harvesting in April and May.

Farmland grew in size as agriculture and domestication increased. Later development led to social differentiation, allowing some community members to engage in off-farm activities such as construction, mining, woodworking, metalworking, trading, stone cutting, and other services. In the period between 4500 and 3200 BC, urban landscapes, such as Jiroft[24], Shahr-e Sukhteh[25], Tape Yahya[26], Tape Sialk (South), Tape Pardis, Tape Hissar[27], and Tape Ghabristan[28] were primarily formed alongside natural watercourses (Ghrishman, 1987; Manuel et al., 2014). There is a general rule for settlement development; the more access to perennial water resources, the greater the potential for settlement development. In this regard, Ghrishman (1987) considers the arid and semi-arid regions of the Central Plateau as one of the most challenging areas in Iran for prehistoric development. According to him, the geography and climate of the Central Plateau were harsh and austere. The oases were spread out over rough terrain; the population was sparse and scattered. Due to the unreliability of water, the urban revolution was delayed, and society remained in a prehistoric state for hundreds of years (Ghrishman, 1987).

Despite all the benefits, living on floodplains had significant disadvantages. Because of drought and flood events, shrinking and disappearing water bodies, landscape degradation, and changes in river courses, most early settlements were intermittently occupied. Lowland alluvial rivers, deltas, and alluvial fans, where early settlements were located, might have undergone aggradation due to changing climates, water volumes, and tectonic movements. In response to sediment aggradation and subsequent incision, a relatively unstable river system emerged, where river courses shifted over time, resulting in river terraces of differing ages. With time, people living on river banks needed to relocate and manage their residences to deal with this challenge. It implies that the locality and population of early communities have changed, as have watercourses. There is some irregularity in the number, size, or function of the settlements on the alluvial fan of the Jajrud River in the Tehran Plain, evidenced by the chalcolithic sites Mafinabad[29] and Tape Pardis (Manuel et al., 2014). This point is also supported by the thoroughly documented site of Cheshmeh-Ali, near Shahr-e Rey[30], which extends from the Late Neolithic period to the Chalcolithic period with more than one phase of settlement.

Floods were one of the most significant events that affected prehistoric Iran's social and demographic development. Geomorphological, climatological, and anthropogenic factors were the primary contributing factors to these events. Although heavy rainfall and melting snow have traditionally been significant causes of flooding in Iran, large river" meander patterns could worsen flooding. In flat areas like alluvial plains, the river flow velocity drastically decreases, and river sediments deposit. Sediment deposition causes the river's elevation to rise, allowing it to flood. Flooding might be caused or exacerbated by climate change, followed by land-use and deforestation changes. Nemati et al. (2020) provided an example of such an event. According to them, Iran's climate changed to a temperate and humid regime in the Late Neolithic and Chalcolithic periods (6200–4300 BC). As a result of this period, the number of early settlements increased, deforestation occurred, and the land was converted into agricultural fields. Floods were caused by both increased rainfall and deforestation. Gillmore et al. (2009) confirm flooding during Late Neolithic Iran through sedimentological and archaeological observations on the fluvial deposits of the Tape Pardis site. Many prehistoric communities (e.g., Tape Zagheh, Sialk, Chogh Bount, Ganj Dareh, Cheshmeh Ali) developed during the same period as Tape Padis; they were likely flooded as well.

The earliest shapes of settlements were very vulnerable to severe climate changes and water shortages over long periods. Walker and Fattahi (2011) have shown that increased aridity slowed the evolution of the landscape and negatively impacted eastern Iranian society. Lawler (2011) suggests that Shahr-e Sukhteh, an old Bronze Age settlement in southeast Iran, was abandoned after prolonged droughts at the end of the 3rd Millennium BC, following the Helmand Delta drying up. This period of drought coincided with the collapse of Bam, a Bronze Age settlement twice the size of Shahr-e Sukhteh (Walker and Fattahi, 2011). The inhabitants of the arid regions began to manage water scarcity by improving their water systems rather than abandoning their homes. Between 2800 and 1100 BC, during the emergence of the first city-states, modest size water systems were designed to collect, store, and supply water, indicating a relatively centralized water management system. One of the most striking manifestations of this trend has been in the west and southwest of Iran, where settlements have been established within the fertile and adequately irrigated province of Khuzestan. In this region, the low-gradient meandering Karun[31], Karkheh[32], Jarrahi[33], Shavur[34], and Dez[35] rivers flow in extensive floodplains, overlain by dense alluvial deposits. Meander cut-offs (oxbow lakes), marshes, and abandoned streams are developed alongside these rivers. This area, however, is susceptible to low, erratic rainfall and drought; mainly irrigated agriculture was feasible. Hence, a complex of water systems, including canals of various sizes (a central canal and a network of secondary, tertiary, quaternary, and field canals), head-gates, distributors, regulators, inlets and outlets, weirs, levees, and storage reservoirs was designed to ensure full irrigation (Tamburrino, 2010).

Water in early historic Iran. Both rural and urban development in Khuzestan depended upon careful water management. Susa, one of the oldest-known proto-cities of the Middle East, occupied the fertile Susiana Plain among the Karkheh, Shavur, and Dez rivers. The formation of Susa followed the abandonment of a nearby city known as "Chogha Mish" This city was a well-organized settlement with water wells, wastewater facilities, cesspits[36], and stormwater drainage systems (Alizadeh, 2008). Ancient canals and waterways were built around Susa to facilitate the transfer of water from the rivers (Viollet, 2017). During rainy seasons and great floods, there was a considerable amount of sediment released into the plain by these rivers (Tamburrino, 2010). In ~1250 BC, the first multipurpose hydraulic structure was constructed to treat and remove particles from water at the

Fig. 2 The remaining of a water treatment system in "Chogha Zanbil" Complex, Khuzestan, Iran. a Front side view: Water was stored and desilted in the reservoir with a capacity of 337 m^3 (10.70 m × 7.25 m × 4.35 m). **b** Back side view: The filtered water was transferred to a pond through nine conduits. When the pond was fully recharged, the filtered water was distributed by a network of canals (Adopted from Naghsh Avaran Toos Consulting Engineers Company, 2013).

"Chogha Zanbil Complex" Elam's religious center (Semsar Yazdi and Askar Zadeh, 2007; Sadr, 2017) (Fig. 2). Water is transferred and collected from surrounding canals into a 337 m^3 water storage (10.70 m in length, 7.25 m in width, and 4.35 m in height) (Ghirshman, 1966; Partani and Heidary, 2017). There was an inlet canal, two sidewalls, and a brick front wall in the reservoir, insulated with a layer of natural bitumen. Water was stored and treated in the reservoir as it passed through various sand and gravel deposits (Gholikandi et al., 2013). Nine conduits at the bottom of the front wall transport the treated water to a basin. The conduits had two inclined surfaces. Each conduit was 0.8 meters apart. Due to the higher elevation of the basin compared to the conduits, earthy materials were removed from the water. The filtered water was diverted to the temple once the pond had been fully replenished. In the temple, water was distributed through canals used for rituals of worship and purification.

In Susa, one of the earliest water-related regulations was unearthed, issued by the sixth ruler of Babylon, King Hammurabi (1792–1750 BC)[37] (Veenhof, 1995). In Hammurabi's Code, water-related provisions are specifically addressed in a few provisions (Gasche, 1998). In this regard, commonalities between Hammurabi's Code concepts and the Achaemenid regulations, particularly the inscriptions of Darius the Great, suggest that they were aware of Hammurabi's Code concepts[38] (Holden, 2019).

Iran's prehistoric and protohistoric societies relied heavily on irrigated agriculture. Hence, major farming communities and proto-cities grew around surface water resources. The greatest challenge to integrated water management was the absence of a central government responsible for solving large-scale water-related problems. For large-scale water management at all levels, there must be a careful consideration of all related aspects, such as technical, institutional, societal, financial, and infrastructural. It was a gap that the Iranians could fill during the Achaemenid civilization.

Water in the Achaemenid Empire. In 550 BC, Cyrus the Great established the First Persian Empire (the second Iranian empire-based Dynasty after the Median Dynasty) known as the Achaemenid Dynasty in the land of "Pars" or "Persis" (Sampson, 2005). The Persians came to power, became the most extensive empire globally, and ended in 330 BC with Alexander III of Macedon defeating Darius III, the last Achaemenid king. With the advent of the Achaemenids, Iran was undergoing fundamental changes. These alterations were visible in many social, cultural, economic, technological, and institutional areas. During their 220 years of rule, the splendid development of the Achaemenids in all domains was largely dependent upon large-scale government-managed waterworks and vice versa. In the following, we provide a brief portrayal of the critical factors and conditions related to the development of water resources in this era.

At the beginning of the Achaemenid kingdom, there were many ethnic tribes around Iran. According to Kuhrt (2013), some people were sedentary, engaged in on-farm (land preparation, cultivation, irrigation, harvesting), off-farm (processing, packaging, storage, transporting, and distributing products), and non-farm activities (construction, mining, woodworking, metalworking, trading, stone cutting, and other services). Some tribes were nomads, guided by tribal laws and traditions. Nomad people were cattle-breeders who moved for pastures (Garthwaite, 2008; Shahpour Shahbazi, 2011). Other nomadic tribes were semi-nomadic. They often stay in a specific place for an expanded time unless drought and water scarcity force them to move. Although agricultural sedentism dominated Iran even before the Achaemenian Empire, nomad tribes played a more colorful role in some facets. Nomadism was an excellent indication of how Iranians adapted to their arid and semi-arid climates. Undeniably, flexibility had a critical role in the nomad's life. Nomads focused on producing various dairy products and agricultures made cereals, fibers, fruits, cottonseed, and flax (Garthwaite, 2008). The main difference between nomadism and agricultural sedentism was that farmers were more dependent on the field than on pasture. Both common denominators were the need to water, a valuable and scarce asset.

Before the Achaemenids, the clans and tribes were commonly vying and struggling to obtain their benefits (Beigzadeh, 2019; Bayani, 2002). Water, land, and pasture were integral to the tribe's lives; they must be fought for, upheld, and defended. Each territory possessed its leadership, weapons, requisite skills, and culture to mount a defense for protecting these valuable resources. Internal and external conflicts were not without consequences. Those led to diminished attention to the nation's entire sectors, causing a mess and destabilization. The Achaemenids, realizing that development in all aspects requires internal security, were able to pave the way for water development by establishing stability.

The key to the Achaemenid rule was the novel innovation of treating various ethnicities with tolerance, equality, and pluralism (Balatti, 2021). Creating unity and security between different Iranian ethnic groups turned a page in the history of Iran,

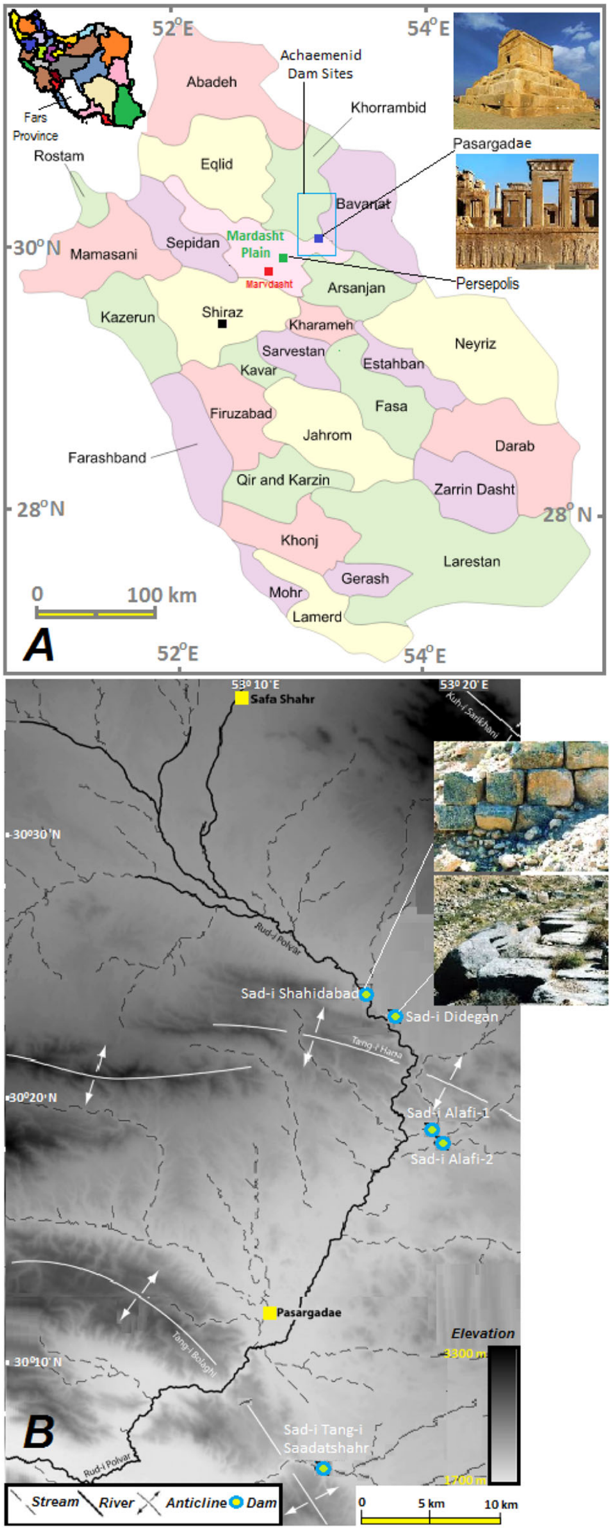


Fig. 3 Geographical location of Pasargadae and Persepolis and the Achaemenid dams in the Marvdasht Plain, Fars Province. A Surrounded by the southern Zagros Mountains, the 160-ha archaeological site of Pasargadae, the earliest capital of the Achaemenid Empire, is located on the Marvdasht Plain in Fars Province. Located 40 km southwest of Pasargadae, Persepolis was an impressive palace complex and the ceremonial capital of the Achaemenid Empire. Shiraz, the capital of Fars Province is located 60 km (37 miles) southwest of the Persepolis ruins. **B** The Pulvar River and its dams, including the "Sad-i Alafi-1 Dam," "Sad-i Alafi-2 Dam," "Sad-i Shahidabad Dam," "Sad-i Tang-e Saadatshahr Dam," and "Sad-i Didegan Dam." Upon passing the tomb of Cyrus, the Pulvar River reaches Persepolis, creating an imperative link between the two sites (Map B is based on the global SRTM DEM created by Ertsen and De Schacht, 2013). Edited by Microsoft paint, Windows 8, https://www.microsoft.com/en-us/windows.

providing partnerships for progress in all dimensions. Concerning the economic, health, cultural, and religious importance of water among Iranians, the Achaemenids perceived that developing water resources has a critical role in creating peace, promoting co-existence, and lasting stability among all Iranian ethnic groups.

Most of the Achaemenid's kings and advisors were shrewd politicians and farsighted state builders. They knew very well that the large-scale development of water was beyond the reach of ordinary people. The construction and management of mega-hydraulic infrastructures were time-consuming, expertize-demanding, labor-intensive, and expensive, requiring a high level of coordination and collaboration that could only be set and enforced by a central governance body. Filling this gap and similar gaps was one of the reasons that introduced a unique system of governance, characterized by a tightly organized, centralized administration. They created a unique monetary system and common language for administration and paid much attention to standardizing units, criteria, and values. Benefiting from such an organized system of governance, the Achaemenids were able to strengthen their water policies. They dug qanats and constructed dams and networks of water canals, drainage systems, and waterways with state-of-art technology and managerial skills, resulting in agricultural productivity, food security, urban development, trade growth, political stability, and cultural adaptations.

There were many crucial centers all around Iran. Ecbatana[39] and Susa were two of them. Two other ones were Pasargadae[40] and Persepolis[41], both located in the heart of the Achaemenid's homeland, the Province of Pars (Yamauchi, 1991). As the Achaemenids strengthened, there was an increasing demand for water supply, irrigation, flood control, and diverting water. Regarding geopolitical, religious, and climatological reasons, all attention was on Persepolis and Pasargadae (Fig. 3). In Susa and Ecbatana, the situation was different. In Susa, water-related infrastructures had already been built by previous states. Ecbatana enjoyed abundant rainfall, allowing non-irrigated cultivation. Undoubtedly, many other water-related facilities had been constructed by the Achaemenids across Iran, either not being studied thoroughly or destroyed utterly.

Where Cyrus the Great performed his coronation, Pasargadae lies on the Marvdasht Plain[42] in present-day Fars Province. In a straight line, Persepolis is 40 km to the southwest of Pasargadae with an altitude of 1770 m.a.s.l. (Godard, 1962). At the beginning of the spring season, when the Persians celebrated their New Year[43] in Persepolis, the Marvdasht Plain enjoyed a mild and pleasant climate. However, unlike the lovely spring, the plain's climate is semi-arid based on today's weather conditions, with an average annual rainfall of 343 mm. The Kor River runs permanently from the northwest to southeast across the plain and discharges into the Bakhtegan Lake. The Pulvar Stream[44], the main tributary of the Kor River, flows through the plain from northeast to south-southwest and flows into the Kor River at Khan Bridge[45] (Shahpour Shahbazi, 2011).

Since the Marvdasht Plain's river level was lower than the surrounding areas, it was impossible to use any water from the streams without artificial assistance and technical installations. Also, the drainage system in mountainous regions was poor, and most basins experienced abrupt floods. The steep slopes of hillsides and small-scale alluvial fans, where the channel conveyance capacity of rivers is low, increase the risk of flash floods. Canal destruction and sedimentation were among the critical problems of floods, so abandoning water canals and building new ones were more comfortable than fixing them. Massive networks of diversion and irrigation canals were needed to divert floodwater and irrigate croplands. Thus, the Achaemenids established many dams, reservoirs, and networks of water canals to keep rivers safe, store floodwater, divert flow, and supply water.

In Fars Province, the "Ramjerd" Dam, "Darius Dam"[46], "Bande-Sang Dokhtaran," and a collection of five other dams, including the "Sad-i Alafi-1 Dam," "Sad-i Alafi-2 Dam," "Sad-i Tang-e Saadatshahr Dam," "Sad-i Shahidabad Dam," and "Sad-i Didegan Dam," were constructed with the Achaemenids on the Kor River headstream (Mays, 2010; De Schacht et al., 2012; Ertsen and De Schacht, 2013; Karami and Talebiyan, 2015). Except for the Sad-i Shahidabad Dam, situated on a perennial river, the rests are now in dry riverbeds. The Sad-i Didegan Dam is an embankment dam with a watershed area of ~46 km^2, constructed in the Early Achaemenid period with earth materials. The dam dimensions are ~105 m in width, 21 m in height, and a crown length of ~105 m[47] (De Schacht et al., 2012). There are traces of a recharging waterway in the upper parts and a control structure used to stabilize water flow (Ertsen and De Schacht, 2013). In the dam's architecture, regular stone blocks were connected with swallow-tailed iron clamps coated by molten lead[48] (Shahpour Shahbazi, 2011). All the stones were local and quarried on the spot. The dam structure is similar to "Sad-el Kafarathe Dam," built in ~the 3rd Millennium BC by the ancient Egyptians for flood control (Smith, 1971).

Another major dam, Sad-i Shahidabad, was constructed on the Pulvar River in the "Tangeh Bolaghi Area" in Fars Province (Ertsen and De Schacht, 2013). This dam has dimensions of ~590 m in width, 15 m high, and a crown length of ~700 m, where its watershed has an area of ~4,900 km. The Sad-i Didegan and Sad-i Shahidabad dams have similar canal designs and control structures (De Schacht et al., 2012). Considering the traditional form of stones, precise engineering, and unique architectural system, it is clear that the engineers who constructed the Achaemenid dams had enough experience to consider various engineering parameters for dam construction.

The Achaemenids realized that rainfall and rivers in their territory were insufficient for a secure water supply. Like other ancient civilizations, the Achaemenids used water-lifting devices for irrigation and domestic water supply. Hand-operated or animal-powered water-lifting machines were standard in Iran. The water-lifting rate for a typical animal-powered waterwheel varied between 480 m^3/d (1.5 m height of water lift) and 240 m^3/d (9 m height of water lift) (Molenaar, 1956). However, well and qanat construction was not economically or technically feasible in a few cases. Therefore, they sometimes supplied water from spring sources through subterranean or open canals. For instance, a long underground channel in the Persepolis Complex transferred the springs' water (Mays, 2010). Waterways were usually excavated into the hill's slope, which dominated the platform to collect and convey rainwater from the mountain to the straightforward, avoiding damage to the complex (Holden, 2019). Canals were coated with tar in individual sections to prevent water seepage beneath the Persepolis platform. Besides, the Achaemenids build levees for flood protection, watermills for grinding wheat, canals for water transport, and reservoirs for storing water (Mays, 2010).

The building of the Marvdasht historical complex and its surrounding hydraulic structures show how the Achaemenids could establish a strong link between science, technology, and culture. They had an excellent background and understanding of hydrology, civil engineering, and other related sciences such as climatic hazards, mining, and urban planning. From the climatological point of view, they knew the rainstorm season in Fars starts at the beginning of November and finishes at the end of April. The snow-melting period begins in March and ends in May. The heavy floods probably occurred in March and April when the snow-melting process followed rain storms. Two of the oldest festivals in Iran, known as "Nowruz" and Farvardinegan (Remembrance Day), were held between March and April. The flood events could have disrupted the ceremonies, so building dams and relevant water systems were necessary.

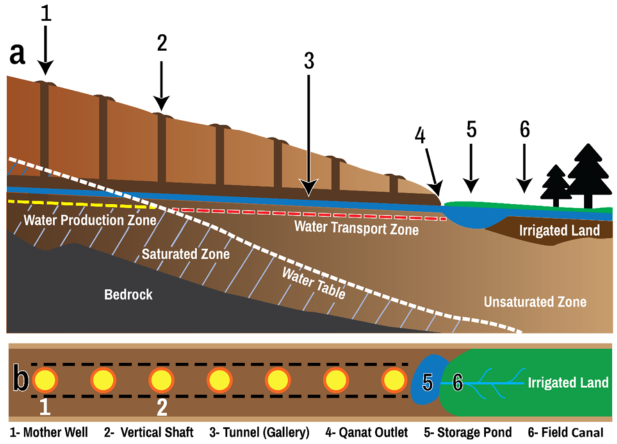


Fig. 4 A simple schematic showing a typical qanat system. a Cross-section: Using simple hand tools, the "mother well" is dug by a crew of skilled qanat diggers to a level below the groundwater table to locate the water table and assess the quality, quantity, and regularity of the groundwater flow. The mother-well depth depends on the water table depth, qanat length, earth slope, and the owner capital for excavation, ranging between 30 m and 100 m. Between the mother-well and qanat outlet, the crew digs vertical shafts at intervals of ~20 to 200 m, with a diameter of 80 and 100 cm. The shafts are used for removing excavated materials from the tunnel, ensuring air circulation, and providing access for repair and maintenance. **b** Aerial view: Tunnel lengths in the Qanat range from a few hundred meters to 100 kilometers, with gradients ranging from 2/1000 to 5/1000. At the outlet, qanat discharge varies from 0.001 to 300 m^3 per hour (on average, 60 m^3 per hour). Edited by Microsoft paint, Windows 8, https://www.microsoft.com/en-us/windows.

Qanat system. Qanat[49] consists of one or more gently sloping tunnels (galleries)[50] and a series of vertical shaft wells, designed to extract and transfer groundwater by gravity to flatter slopes, particularly for use in arid and semi-arid regions (Fig. 4). The tunnel has a semi-elliptical cross-section with a height and width of about 1.2 and 0.8 meters, respectively (Beaumont, 1971). According to Farzadmehr and Nazari Samani (2009), the tunnel slope should be between 0.3 and 0.5%, ensuring a balance between excessive erosion and sedimentation of the tunnel bed. Part of the tunnel excavated through an aquifer's phreatic zone is the water-producing zone, and another part that transfers water to the ground surface is the water transport zone (Salvini, 2001). To decrease water infiltration, the tunnel bed is covered with impermeable materials such as Sarooj[51] and compacted clay (Pouraghniaei and Malekian, 2001).

Traditionally, finding a reliable groundwater source has been the first step in the qanat construction. To locate a qanat, the knowledge and expertize of the qanat digger[52] are of paramount significance. The ancients presumably knew that groundwater could be obtained from foothills, wadies, dry riverbeds, intermountain basins, and alluvial fans (Semsar Yazdi and Labbaf Khaneiki, 2016). Landscape, anomalies in soil color and moisture, seepage patterns, vegetation cover, and spring discharge were conventional indicators used by diggers. Considering groundwater availability, the first and deepest shaft named the "mother-well"[53], at a depth between 10 to 250 m[54], has been sunk into the saturated zone for locating the water table and checking groundwater quality, quantity, and flow regularity (Ahmadi et al., 2010). Then, along a line between the mother-well and the qanat outlet (appearance)[55], the crew dug a series of well-like shafts[56] with different depths at intervals of 20 to 200 m to remove the excavated materials from the main tunnel, air circulation, and provide access for repair and maintenance. If the soil is loose and unstable, the tunnel and shaft lining is necessary to improve the qanat durability. The excavated soil is dumped all around the shaft opening during the digging process to prevent surface runoff from entering the shaft. The spoil from these access shafts creates the distinctive doughnut-shaped rings that characterize the qanat lines (Semsar Yazdi and Askar Zadeh, 2007). Relying on gravity, water flows continuously, sometimes over a long distance, from the qanat outlet to water consumption areas (farms, gardens, and settlements) and water storage facilities (Ab-Anbar[57] or Yakhchal[58]) through a network of open canals (Labbaf Khaneiki, 2020). The distance between the mother-well and the qanat outlet varies from tens of meters to several tens of kilometers, reaching about 80 km in one of the longest qanats in Zarach City (Kobori, 1973; Eghtedari, 1974). The climatological, topographical, hydrogeological, and technological factors control the qanat discharge, which can range from 0.001 to 300 m^3 per hour (on average, 60 m^3 per hour) (Kuhrt, 2013).

The origin and outspread of the qanat have been discussed by many researchers, such as Kobori (1973), Wilkinson (1977), Goblot (1979), Salvini (2001), Boucharlat (2003), and Magee (2005). However, as archaeological and non-archeological resources provide scant information on the qanat's history, this field still lacks a widely accepted hypothesis. Prior to the advent of advanced technologies, historical texts were the only sources of reference for judging. In one of the oldest historical books, the Greek historian Polybius (200–118 BC) describes qanats during the Antiochus campaign[59] against Arsaces[60]. Although this text discusses the use of qanat technology in the Seleucid period, it appears that this technology was passed down from the Achaemenids to the Seleucids. In addition to Polybius' historical document, the fact that the majority of qanats are found in Iran has played a decisive role in drawing the attention of researchers to Iran as the place where the system originated.

Hogarth (1904) provides one of the earliest classic hypotheses about the qanat's origin, stating that it was introduced by the Achaemenids in the sixth century BC. Hogarth's assumptions met with approval and were reiterated by Laessøe (1971) and Wilkinson (1977). Goblot (1979) asserted that the ancient kingdom of Urartu was the cradle of the qanat technology, but the Achaemenids transferred it east and west. Goblot's hypothesis is proposed based on some inscriptions on a badly damaged tablet[61], which describes the qanat system as seen by Assyrian King Sargon II[62] in his Eighth campaign against Ulhu[63], dating back to 714 BC. Gobot's hypothesis, counting the theory that qanats originated from mining, had both pros and cons. In one of the most prominent criticisms, the rereading of the tablet revealed that the text does not refer to qanat; it may be caused by an inaccuracy in the translation of the old text (Salvini, 2001). Nonetheless, there is a lack of information regarding qanats during the Achaemenid period in Iran, so that, further investigates are still required to propose a robust hypothesis.

According to Magee (2005), a more likely location for the emergence of the qanat is in the southern regions of Iran. It is also likely to have occurred in neighboring parts of Pakistan and the Arabian Plate. Magee believes a hot and arid climate prevailed in the Middle East during the Late Second and Early First Millennium BC. The sediment analysis and fossil records in some parts of Pakistan and Turkey confirm this hypothesis (Luckge et al., 2001). There is also evidence that settlements in southeastern Iran declined during this period as well (Wilkinson et al., 2012). In this regard, qanat may be a reaction to climate change and water shortage. However, accurate localization, dating, and descriptions of archeological evidence were necessary to evaluate this possibility.

Within the past decades, modern archeological and chronological investigations have provided new insights into the qanat's origin and outspread. In 2002, al-Tikriti conducted a number of archaeological and stratigraphic examinations in the Oman Peninsula that revealed one of the earliest evidence of qanat systems dates from the Iron Age II, roughly between 1000 and 800 BC, around a few centuries prior to Achaemenid rule. al-Tikriti's description of Oman's qanat systems revealed that, in contrast to the Achaemenid qanats, the Oman Peninsula qanats had a simple structure, a short length, and shallow depth (al-Tikriti, 2002). Apparently, these qanats served as a template for more sophisticated systems that followed. The time gap between the qanats of the Arabian Peninsula and Iran has also been narrowed as a result of other investigations. Archeological and geological observations conducted in the Khargushan region[64] of Bam revealed several sites dating to the mid-first millennium BC or slightly older. The Bam site was home to several surface channels and numerous qanats, but many of these structures collapsed by the earthquake. However, the chronology of at least two qanats indicates a pre-Achaemenid date between 440 and 200 BC for both qanats (Boucharlat, 2014). Considering the fact that the qanat technology is well-known in southeastern Iran and southeastern Arabia, it is interesting to speculate whether the existence of qanat technology in Oman and south of Iran may be a result of the close social ties between Iranians and Omanis on both sides of the Persian Gulf.

In clarifying the global distribution of qanat in Iran, Afghanistan, Iraq, Oman, Saudi Arabia, Egypt, Jordan, and other regions, a better foundation has been provided for further discussion regarding their origin and spread. Boucharlat (2017) assumes that the qanat evolved over two different periods of time based on its architectural and hydraulic characteristics. The initial phase generally dates back to the first millennium BC, when primitive qanats, with shallow mother-wells and short galleries, extracted water from shallow aquifers. The second stage is characterized by much greater, deeper, and more complex qanats, designed to extract water from deep aquifers (Boucharlat, 2017). Following this proposal, two different paradigms have been expressed by Avni (2018) as follows [i] qanats were invented in one core region, either in Iran or Oman, and later diffused to large parts of Eurasia and beyond; [ii] In different areas, these systems have been developed independently. In general, Avni's hypotheses are supported by some and opposed by others. For instance, a geomorphological and archeological study of the Ain-Manawir qanat systems in the southern Kharga Oasis of Egypt suggested that the Achaemenids played an influential role in developing water resources and allowing permanent settlements. In this site, an increase in the number of water structures was observed around the qanats that were dated at the same time as the Achaemenid Emperor (Wilkinson et al., 2012). However, it they could be constructed separately in the second half of the fifth century BC.

Table 1 Advantages and disadvantages of the qanat system.

	Advantage	Disadvantage
Social and Government Aspects	Qanat enabled nomadic tribes to have a settled life and engage in social activities. Application to transport water over long distances; Allowing the government to utilize barren lands purposefully. Making a significant relationship between the government, local owners, and farmers for constructing, maintaining and reviving qanats. Applying digging-related experiences in the military to build underground tunnels for smuggling and defensive purposes; allowing the Achaemenids to extend their authority to farther regions	Creating controversy over the approximation of the buffer zone, water allocation and distribution
Agricultural and Economic Aspects	The emergence of the whole-season agriculture	To be relatively time-consuming, labor-intensive, and expensive for the construction, maintenance, and repair of qanats
	The increase in agricultural products, food supply, and income; allowing the people to be empowered socially and economically. Proving service to many caravans, on oases along the Silk Route, developing economic, and cultural trade.	Not appropriate to supply water for modern large-scale agriculture
Hydrological Aspects	Insensitive to seasonal and other short-time changes in weather Extracting groundwater as a renewable resource without making rapid drawdown in the aquifer	Having a non-stop discharge during all seasons Not possible to construct in flat areas
	Supplying cold freshwater with low turbidity, and water loss. Using the energy of gravity for water transferring without the need to pump or other forms of energy. Providing energy through watermills Collecting surface runoff through the vertical shafts and reduce the risk of flash floods. The ability to store the qanat water into small reservoirs for later use.	Extreme floods and earthquakes can severely damage, or obliterate the qanat shafts and tunnel.

While qanat archeology has made significant advances, there are numerous unanswered questions. Hundreds of years before the rise of the Achaemenid Empire, could qanat serve as anything other than a source of water (e.g., air conditioning)? Is it possible for qanats to be created or evolved independently in different parts of the world? Is it possible for qanats to develop in more than one stage? In this regard, the deeper we understand archeology and related sciences, the more likely we will be to determine when and where qanats originated, the stages of their evolution, and their impact on the lives of various societies.

From a geographical view, most ancient qanats were constructed in the central, eastern, and southeastern Iranian Plateau with inadequate internal waterways (e.g., in present-day Markazi, Kerman, Hormozgan, Sistan and Baluchestan, Khorasan Razavi, South Khorasan, Isfahan, and Yazd provinces). According to Briant (2002), further expansion of qanat technology in Central Iran led to the emergence of the whole-season agriculture, thus ensuring an increase in agricultural intensification, food supply, and income. The qanat practice, however, was not common in water-rich regions (e.g., Gilan, and Mazandaran) unless surface water resources were fully exploited or depleted during long-term droughts.

There are advantages and disadvantages inherent in the qanat, as with any other water-related system (Table 1). In contrast to a water well, the relationships between qanat owners, users, and service providers are often complex and intertwined; a qanat would have been excavated over a long distance, covering the lands of hundreds of families with unequal shares and rights (Kobori, 1973). In some cases, the linear structure of the qanats led to controversy in water distribution from upstream to downstream, particularly during times of water shortages· Water ownership was also a concern when a qanat, built by a person for a specific purpose, passed underneath another person's field. The approximation of the buffer zone[65] along the route of each qanat and assessing the owner's contribution in digging, maintaining, and restoring a qanat were other sources of friction. These challenges existed not only in the past but also in the present. The Achaemenids were aware of this and made efforts to protect, clean up, and rehabilitate qanats through peaceful collaboration. The Achaemenids, also, possessed extensive knowledge of geodesy, hydrometry, and hydraulic engineering, which enabled them to address problems related to the ownership and allocation of qanats (Bensi, 2020). It is also important to note that due to the people's dependence on qanats, the Achaemenid government also implemented several remuneration and incentive policies for renovating abandoned qanats. As one of the motivational policies, revivalists and their descendants were exempt from paying taxes for the next five generations (Semsar Yazdi and Askar Zadeh, 2007). According to Nathanson (2013), Zoroastrian priests[66] have always encouraged farmers to produce more than their demand by developing their land and water resources[67]. These incentives could encourage people to revive their natural resources and improve their living environment by working together.

Water in the Seleucids Era and Parthian Era. Following the conquest of Iran by Alexander the Great in 330 BC, the Iranian satraps[68] were governed by various Greek Satraps forming the Hellenistic Seleucid Empire and then the Parthian Empire[69] (Curtis, 2007). In this era, Iran was nominally a united country composed of some semi-independent and sometimes scattered states. The central government did not interfere in the internal affairs of the states except in cases related to security and peace. Besides, the Parthian emperors did not promote a single religion. Hence, there were no single and fixed judicial principles. These factors reduced consensus, unity, and cooperation among Iranians. In the Early Parthian period, the Parthians could not manage water-related structures like the Achaemenids. Qanats and other water-related facilities seem to have been abandoned or destroyed due to internal strife[70] and wars with Rome (Ashrafi and Safdarian, 2015). According to Wenke (1981), agricultural development in the first two centuries AD was concentrated in certain well-watered regions. Subsequently, agricultural activities decreased in water-scarce areas due to poor water resource management, causing environmental degradation, a decline in rural family income, a rise in unemployment, and growth in rural-urban migration. Along with the migration, the number of urban centers increased; urbanization changed society and the economy. Trade and manufacturing activities reached their peaks[71]. Later, the Sassanids made these factors more complete and purposeful by expanding agriculture and creating a suitable administrative organization.

Water in the Sasanian Dynasty. The Sassanid's regulations had excellent attention to groundwater, especially to issues concerning the management of qanat. The Sasanian Empire realized that the water resources administration provided them the strength, stability, and durability. Hence, they established the first specific department of water called "Diwan-e Kastfezoud" (also named "Diwan-e Kast-Afzoud"[72]), and the respecting regulation was called "Namak" (Ali Abadi, 2005). The department's duties were developing, managing, and protecting water resources, collecting water tax and tribute from all the territories, constituting rules, and solving water-related conflicts. In this respect, a set of 150 legal documents, written down in the Pahlavi language, related to judgments, contracts and possessions, tax receipts, and lists of the farmland properties has been discovered, translated, and printed, confirming the ability of the Sassanids in structuring their domain (Rezakhani, 2008 and 2017). Besides, water rights cases and legal frameworks for water canals and qanats have been mentioned in the Matigan-i Hazar Datistan[73].

Water resource management in the Sassanid Era. As mentioned above, the department of "Diwan-e Kastfezoud" in the Sassanid period, similar to the ministry of water resources in the current modern countries, was responsible for the development and management of water resources of the empire. The Sassanids tried to change the ownership of qanats from private to the community (Gholikandi et al., 2013). Some landlords partially or totally donated the qanat paths under their lands to the community they served. During this period, water management was well-organized and coherent at all levels, administratively and operationally. The management roles varied not only in time and place but also in function as the population density and the production of cash-crops increased. There was generally an increase in governmental integration and coordination and an increase in investment in planning, organizing, and controlling water resources in areas with rapid growth in the population[74] (e.g., Gur-Ardashir-Khwarrah[75], Bishapur[76], Darabgard[77]) and heavily irrigated agricultural heartlands (e.g., the Miyanab[78], Susiana, and Mesopotamian Plains (Moghaddam and Miri, 2007; Neely, 2011). Rice, sugarcane, cotton, and orchard fruits are among the export crops that have benefited from improved transportation and internal security under better administrative control (Soroush, 2014). It would be necessary, however, to establish irrigation systems, qanat networks, weirs, barrages, and canals to provide sufficient amounts of water for the cultivation of these crops (Lambton, 1953). Some of these infrastructures were time-consuming, laborious, and capital-intensive in building, requiring extensive skills in hydraulic engineering, geodesy, hydrometery, stone masonry, and other construction disciplines. However, the Sassanids did not need to build large-scale water structures everywhere through a deliberate governmental plan, for instance, where winter-cultivation of barley and wheat was common or where Persian gardens (Paradise[79]) were developed. These systems, while presumably under the oversight of the government, were managed locally. In a few cases, summer cultivation was practiced using simple water-lifting devices or runoff harvesting, independent of large dams and weirs. As a result, effective water management was sometimes achieved without large-scale structures. Another situation might arise when a large-scale hydraulic system does not appear being from a top-down scheme or their management oscillates between local and imperial administrations. It has been pointed out by Hunt (1988) that the Nahrawan Canal[80], a significance water transport system in central Iraq, demonstrates a unique example of a hydrological structure from within Sassanid territory that is not entirely the product of a top-down imperial administration. In such cases, locals took advantage of their capacities to sustain their water resources consciously. According to Wilkinson et al. (2012), not only for Iran but also more broadly, it may be necessary to shift the focus away from water and power and towards a deeper understanding of water management, such as local management within an imperial framework.

It was a characteristic of the Sassanid government not to exercise power over people to manage water resources in a top-down manner. The extreme level of government authority over water resources necessitated the establishment of an absolute tyranny over the majority of society. The Sassanids, in turn, developed their water resources in accordance with state/district and local norms for owning, managing, sharing, and preserving water resources. Similar to the Parthians and the Achaemenids, water and land ownership in this era was in the hands of both the government and the private sector. As a private owner, one can own both land and water, or own water in a collective ownership arrangement without owning land (Daryaee, 2014). Wealthy landowners sometimes divided their lands into smaller parcels and leased them to sharecroppers at a fixed rate for a certain period of time. In general, the rental rate was estimated based on the land value and the water availability. As a result, some of the costs associated with the construction and maintenance of hydraulic infrastructure were covered, and sharecroppers' agricultural taxes allowed landowners to invest in local water infrastructure, even in places with less favorable conditions for agriculture.

At the government level, water agents[81] and administrators[82] were responsible for assessing water resources, preparing reports, calculating and collecting taxes, and addressing water-sharing challenges, particularly during water shortage periods. It was common for managers to interact directly with sharecroppers and professionals working to [i] manage village-related affairs[83], [ii] protect and guard water infrastructures[84], and [iii] divide water[85]. However, water administration was a critical job, requiring good education, skills, justice, and morality. The main burden of the daily management of water involving developing and maintaining water canals, irrigation, and many other necessary actions, was on the shoulders of peasants[86] and agricultural laborers, who constituted the bulk of the population. As the Sasanian economy relied on farming, the peasants, irrigators, and water entitlement holders were more respected than in the Parthian Era. The Zoroastrian priests also emphasized the importance of peasants. They encouraged landowners to dig qanats, convert barren lands into fertile farmlands, and plant fruit trees (Daryaee and Omidsalar, 2004). It is important to note that in the ideological system of the Zoroastrian religion, one of the three "Holy Fires[87]" called "Adur Burzen-Mihr"[88] was associated with the farmer class[89]. However, after developing other religions like Christianity, Manichaeism[90], and Mazdakism[91], the degree of connection and participation in all water-related activities decreased.

Table 2 List of dams (weirs) constructed by the Sassanids.

Name	River	Description
Polband-e Dokhtar	Karun River (Shushtar)	Polband-e Dokhtar is one of the largest Sassanid Weir-bridge in western Iran, built over the Kashkan River. The weir, with a length of about 720 m and height of about 30 m, is made of brick, dressed stone, rubble, lime mortar (in piers and foundations), gypsum mortar (in arches), mud, metal clamps (iron and lead), and Sarooj. The weir-bridge was a part of the Royal road, extended from Istakhr[a] and Ctesiphon[b].
Band-e Kaiser (Valerian Weir-Shadorwan Weir-Polband-e Shadorvan)	Shoteit River (Shushtar)	Band-e Kaiser, on the north-west side of Shushtar, was built on the rocky bed of Shoteit River, from east to west, nearly 300 m east of Mizan Weir.
Band-e Mizan	Gargar River (Shushtar)	Mizan Weir, with a length of 390 m and a height of 4.5 m, was built within a diagonal wall plan, in the North of Shushtar to divert the Karun River water to its branches (i.e., Gargar and Shoteit). Remained walls confirm the existence of watermills in the past on the weir's eastern section. In the western part of the weir, an octagonal tower named "Kolah Farangi Tower" is built to monitor the process of weir design and construction. An octagonal tower called "Kolah Farangi Tower" is created to monitor the operation of weir design and construction.
Band-e Gargar	Gargar River (Shushtar)	Gargar Weir, in the northeast of Shushtar, extends from east to west. The weir dimensions are 83 m long, 12 m wide, and 6 m high. This weir is constructed to divert the Gargar River water to the watermills, residential areas, and irrigation canals. The Gargar connects the Karun in Band-e Gheer, 44 km south of Shushtar. Gargar Weir was renovated in the Safavid Era.
Band-e Borj-e-'Ayār (Sabei Kosh)	Gargar River (Shushtar)	Borj-e-'Ayār weir, 7.30 m long and 3.50 m wide, lies across the Gargar River, in the southeast of Shushtar. There is a pond related to the Sabein (Mandaeists[c]) Temple, several historic watermills, and related canals around the weir. The weir was constructed to raise the water level in irrigation canals and provide water for watermills and temple. A small part of the weir is currently preserved, and others are ruined due to road construction.
Band-e Khoda Afarin (Band-e Mahibazan)	Dariyon River (Shushtar)	Khoda Afarin, with a length of 500 m and width-height of two meters, was built south of Shushtar to raise the water level in irrigation canals and link between two sides of the Dariyon River.
Band-e Lashkar (Polband-e Darvâzeh)	Dariyon River (Shushtar)	One of the famous hydraulic structures attributed to the Sassanids is Lashkar Weir, which diverts water to the lands in the south of Shushtar. This structure has 104 m in length, eight meters in width, and 11 gates, stand on solid columns of mortar, brick, and stone.
Band-e Sharabdar	Dariyon River (Shushtar)	Sharabdar Weir, with a length of 35 m, a width of 2 m, and a height of one m, lies in an east-west direction across Raghat Stream[d]. This weir has been built to adjust the water level in irrigation networks.
Band-e Kavar (Band-e Kuar, Band-e Bahman)	Qara Aghaj River (Kavar)	This weir is along the Shiraz-Firuzabad Road in Fars Province, spanning the Qara Aqaj River that flows towards the Persian Gulf. With a length of about 130 m and a height of about 9 m, the weir was constructed to raise the Qara Aghaj water level and to direct its flow to Kavar Plain through a canal built in the weir's eastern corner. The weir materials are pieces of natural mountain stone and mortar.
Polband-e Dezful	Dez River (Dezful)	Dezful weir-bridge, with 22 arches, was set up over the Dez River to link the western and eastern parts of the city and provide water for agricultural areas and gardens of Dezful. Although the weir strong and durable structure, it was substantially damaged by a great flood in 1903.
Band-e Khak	Dariyon River (Shushtar)	Khak Weir, at the southwest of Shushtar, was constructed to prevent the Dariyon River and its neighboring plains from flooding and divert water to its branches. This weir was damaged during road construction activities.
Band-e Ahvaz	Karun River (Ahvaz)	This weir is across the Ahvaz Anticline over the Karun River. The weir collapsed at an unknown time in antiquity. At present, only the wall bases of the weir and traces of mills on the end walls of the weir have remained.

[a]Istakhr" or "Estakhr" was the capital of the Sasanian Dynasty, located 5 km north of Persepolis.
[b]Ctesiphon was a royal capital of the Parthian and Sassanids, located along the Tigris, 32 km southeast of Baghdad.
[c]The Mandaeists follow a monotheistic and gnostic religion, living around rivers in the southeast of Iraq and southwest of Iran.
[d]The Raghat Stream is one of the branches of the Dariyon River.

Weir-Bridge construction in the Sassanid Era. The Sassanids tried to be an urban dynasty by building and rebuilding many cities. They constructed many weir-bridges[92] in Persian and Roman styles (Table 2). The doctrine of urbanization allowed them to acclimatize with Roman technology. Meanwhile, trade played a significant economic and socio-cultural role in thriving the cities. At this time, Shushtar[93] and Dezful[94], because of their geographical situation, mighty rivers, and agricultural lands, had a unique chance for development[95].

The first multipurpose weir-bridge, called "Band-e Kaiser"[96], was built by the Sassanids in the north-west part of Shushtar over the Shoteit River, the main branch of the Karun River. This weir was used as a bridge for passing, regulating the water level, and diverting water to the Dariyon River during water level rises in the Karun (Encyclopedia Iranica, 2020). It had 43 little arches, 44 central arches, 543 m long, 10–15 m wide, and 8 m high, built with sandstone blocks, river stones (pebbles), mortar, and metal clamps. The basic structure and material used in this bridge show

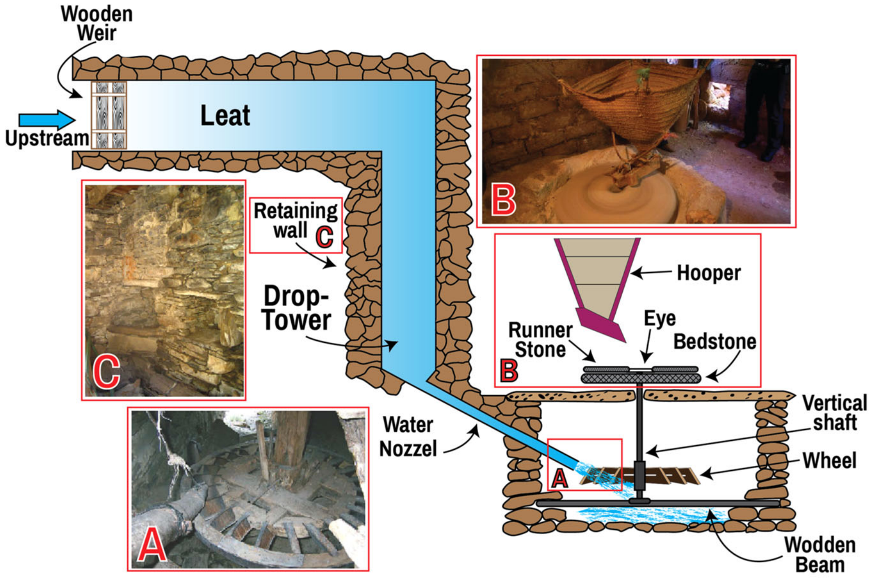


Fig. 5 Structure of a typical horizontal watermill in Iran. The water from the leat is dropped into a vertical chimney known as the "Drop Tower." Water rushes down into a nozzle near the bottom of the Drop Tower; this constricts the jet directed to the water wheel. The water power from a horizontally set water-wheel is transferred to the millstone through a vertical shaft. **A** Water nozzle and horizontal wheel. **B** The position of the lower (fixed) and upper (running) millstones, the feeder hole (eye), and grain hooper. **C** The structure of a conglomerate retaining wall on the outer facade of the millhouse rooms. Drawn by Microsoft paint, Windows 8, https://www.microsoft.com/en-us/windows.

the bridge was designed and constructed with Roman soldiers' labors, captured after Valerian's defeat at the Battle of Edessa in 260 AD (Saeidian, 2013). Band-e Mizan is another well-kept Sassanid weir that diverts the Karun River water to its branches (i.e., Gargar and Shoteit) with a proportion of two to four, respectively. The weir includes nine sluices (mouths) of different sizes[97], made of cut sandstones with mortar branches. Some records show both the Mizan and Kaiser weirs were renovated by the Safavids[98] (1501–1736) and Qajars[99] (1873–1909).

Watermill construction in the Sassanid Era. Watermills[100] are among the earliest hydro-technological structures used by the Iranians to facilitate grinding grains. Earlier grinding was accomplished mainly by animal power[101]; windmills were not typical[102]. Before the advent of watermills, peasants were forced to wait over longtime to grind their grains[103]. In the presence of watermills as machine-driven, cost-reducing, income-generating, time-saving, and high-capacity technology, villagers could increase the size of their lands, and millers were capable of mass grinding.

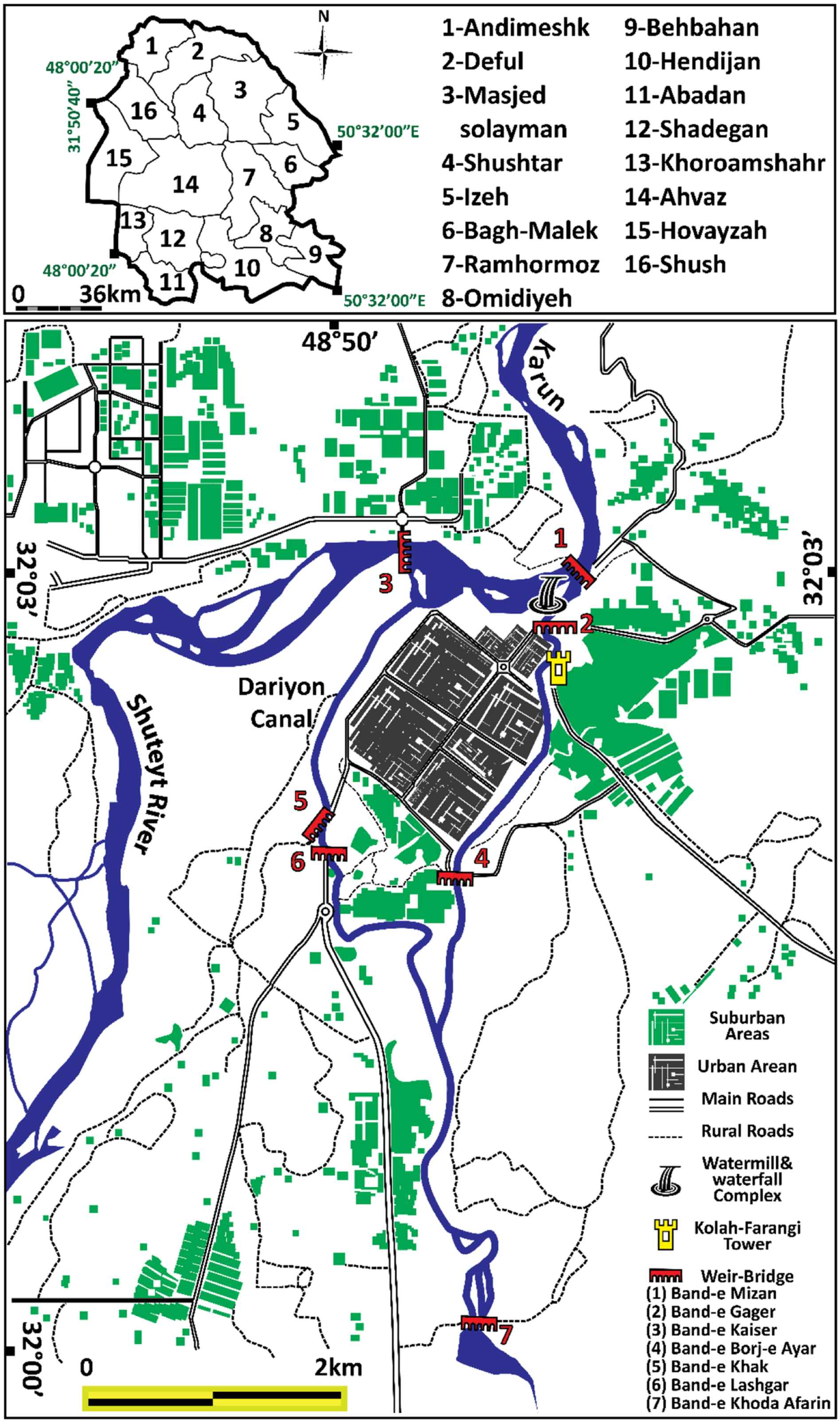
The early spread of watermills in Iran dates back to the Sassanids, especially at the time of King Shapur I[104], Shapur II[105], Kavad I[106], and Khosrow I[107] (Saliba, 1995; Djamali et al., 2017). In this era, farming and agriculture were the basements of the economy. Watermills were one of the most significant components of an intricate network between local water suppliers, grain producers, processors, and consumers in this context. These fulfilled many roles in economic expansion, urbanization, and rural development. The Sasanian's knowledge and experiences in hydraulic structure design made it conceivable to generate power using water flows.

Since the Sassanid Empire, "Greek Mill" and "Roman Mill" have been used to meet the needs. The so-called "Roman Mill" features a vertical wheel rotating about a horizontal shaft. Unlike the Roman type, a "Greek Mill" is powered by a flat wheel, turning around a vertical axle or shaft without setting up gears. This type is generally powered by small water volumes directed at high velocity (Weaver and Pinder, 1963). An inclined aqueduct diverts a proportion of water from a river toward the watermill in these mills. From a height of one to 20 m, the water drops into a reverse cone-shaped water tower to provide a pressure head for driving the wheel. At the bottom of the water tower, a convergent nozzle with varying cross-sectional areas ejects the water to the mill wheel. The flow volume and velocity depend on the water tower[108] and nozzle diameters[109]. The force of rushing water keeps the wheel and runner stone turning around. The bedstone is fixed and more resistant to impact forces than the runner stone[110]. There is a central hole[111] in the turning stone by which the grains fall into the gap between millstones. The grind fineness (or coarseness) is determined with the gap size and turning speed. The turning stone speed depends on many factors, such as the size of millstones[112], wheel design, and water discharge (Fig. 5).

Greek mills have been so welcomed by the Iranians (Saeidian, 2012). Greek mills are simple, low-cost, and easy to construct, operate, maintain, and repair. Besides, these mills are more secure than Roman ones against seasonal fluctuations in river discharge and flash flood damages. However, such mills have the disadvantage of low efficiency, only ~15 to 40%[113]. Hence, these machines grind small amounts of grains (Pourjafar et al., 2010).

Archeologically, the most robust evidence for the Sassanid's investment in building mills is available in the "Shushtar Historical Hydraulic System[114]" (Fig. 6). Located on the east side of Shushtar, there is a cluster of ~40 watermills along the Gargar River[115] (Harverson, 1993). These structures consist of one or two domed rooms and narrow corridors made of cut sandstone and baked brick. The mills are fed by three tunnels called Boleyti, Dahan-e Shahr, and Se-Kureh. Although large parts of the mills were lost over time, the remains were renovated recently as "Shushtar Cultural Heritage" to attract tourists.

Greek watermills, such as those constructed in Khuzestan, Ilam, Fars, and Khorasan, were built below weirs. A typical style was pair watermills in which two sets of watermills, with one headrace, were used in two neighboring rooms separated by a



wall. This mill was designed for grinding two kinds of grains simultaneously. In fast-flowing permanent rivers, a string of water-tower mills, fed by a small canal system, was occasionally constructed at irregular intervals ranging between ~50 m to 1500 m (Weaver and Pinder, 1963; Harverson, 1993). The remnants of a string of 22 pre-Islamic water-towers, covering a total distance of ~6.5 km, are traceable in the Deh-Luran Plain[116] (Weaver and Pinder, 1963). Other examples can be seen in Jiroft[117] (50 mills), Nishabur[118] (40 mills), and Hamadan (20 mills) (UNESCO, 2008).

In some arid regions of Iran, where large permanent rivers are lacking, one or several water-tower mills receive waterpower from a qanat system. Such hybrid systems have been built into qanats with sufficient slope and flow velocity near the lower end of their

Fig. 6 Historical hydraulic structures of the Karun River in Shushtar districts, Khuzestan Province (Adopted from UNESCO MAP of Shushtar under CC-BY-SA license). As shown in this picture, at the north of Shushtar, the Karun River is divided into the eastern Gargar River and the western Shoteit branches. These branches join together in the Band-e Gheer Weir again. The hand-dug Dariyon Channel, with a length of 2.5 km, was excavated downstream of the Mizan Weir to irrigate the land between the Gargar and Shoteit rivers." The Dariyon River is also divided into two branches in the Band-e-Khak. The main branch goes towards the south; it joins the Shoteit River after 33 km in the Arab Hassan Weir. Another branch flows toward the Gargar River. Gargar, with a length of 80 km to 100 km and a width of 20 m to 90 m, is the most significant human-made watercourse in Iran, and its original construction dates back to the Early Sasanian period (Woodbridge et al., 2016). Other names of this river are "Do-Dangeh" and "Mashreghan." The primary function of the Gargar was to irrigate agricultural fields in the south of Shushtar and supply water for residential areas. Adopted from UNESCO MAP of Shushtar under CC-BY-SA license. Geo-referenced using ArcGIS version 10.2 for desktop, https://www.arcgis.com/index.html.

tunnel. The sudden drop of water from the water tower provides a significant driving force for water to transport. As qanat watermills need the elevation difference to turn the wheel, the watermill should be constructed under the qanat's tunnel to enable full water force. Some of these mills are visible in Meybod[119] (Saeidian, 2013), Deh-Luran (Weaver and Pinder, 1963), Ardestan[120] (Harverson, 1993), Sarvestan[121] (UNESCO, 2008), Kashan[122] (UNFAO, 2014), Taft[123] (Papoli Yazdi and Labbaf Khaneiki, 2004), Aradakan[124], and Kerman[125] (Papoli Yazdi and Labbaf Khaneiki, 2000).

Qanat-based watermills can be regarded as an appropriate technology for sustainable development. They have strengthened agricultural livelihoods and food security in central and eastern Iran, where watermilling capacity is inadequate to meet needs. This technology has given local farmers more control over the time, cost, and final product pricing. In addition to grinding, the qanat mills had other functions such as [i] increasing water velocity of moving towards agricultural lands, [ii] decreasing water temperature and evaporation rate, and [iii] covering the qanat's operation and maintenance costs[126].

In Iran, Roman watermills have been chiefly constructed along large rivers, such as "Zayandeh-rud[127]" and Karun. Occasionally, a complex of Roman watermills was built in different sections of a river corridor. Midstream watermills were operated in the dry season and riverside in both wet and dry seasons. Roman watermills were customarily set into two primary levels; a basement for housing the drive system (wheel-house) and a top floor for millstones (grinding room). The grinding room roof was occasionally domed, allowing the air to circulate and light to transmit through the dome openings. The packs of grains were stored in an attic, connected to a hopper to pour grains into the millstones. One of the oldest stream mills[128], dating back to the Sassanid Empire, was constructed in Dezful City[129], at the downstream side of the "Sassanid Bridge[130]" along the Dez River (Eghtedari, 1974; Saeidian, 2012).

The Sassanids could introduce a cost-effective, eco-friendly, and sustainable technology to the Iranians through watermills. Flour made by a watermill was tasty and fresh; it was kept for years without spoiling. It was very prevalent for a mill to being used for centuries. If one mill was severely damaged, another mill would be built on the site. Until the middle of the twentieth century, watermills were a vital part of the country's socio-economic development. Before World War II, Iran was a special grain exporter, but in 1941 it faced a severe famine. More deprived people wanted to solve their economic problems by eliminating inflation and food supply, especially flour and bread. Maybe from this point, the idea of extensive reforms crossed the Second Pahlavi's mind. After the "White Revolution," he rapidly changed the economy, lifestyle, and urbanization. Traditional watermills failed to guarantee an adequate supply of flour and disappeared due to technological advancement. In Iran, a small number of watermills are still producing flour. Two well-known ones are the Kakhak Watermill in Khorasan Razavi Province and Askzar Watermill in Yazd Province. The number of operating watermills in Iran is minimal compared to Afghanistan, India, and Nepal. Given that old watermills are still seen in many cities (Table 3), these systems can generate green energy after rebuilding and reviving.

Obviously, the Sassanid's achievements in developing, managing, and protecting water resources, as well as collecting water taxes and tributes from all of their territories, were somewhat higher than those of the Achaemenids. The Sassanids were noted to be the longest-lasting Persian Empire (427 years), with a brilliant framework for managing water, both imperially and locally. Their advances in water-related fields, however, did not occur in a vacuum; they were certainly influenced by other areas of science, technology, engineering, culture, and government management, developed by their predecessors or other civilizations. In the same way, the Sassanids provided opportunities for future generations. As discussed by Boucharlat in 2012, regardless of the scale of the systems and whether these systems have been established under the supervision of the imperial government or not, the role of these systems in creating water resource sustainability in Iran and other nations is crucial.

Water in the Islamic Era. Although the Sasanian Era was a golden age for the Iranians in terms of agricultural activity, urban development, and economic expansion, it was followed by a challenging transitional period, particularly in southwestern and western Iran[131], the central part of "the Sassanid Empire's agricultural backbone". The exhaustion of the Iranian army through Sassanid-Byzantine wars (602–628 AD), rapid turnover of rulers, the growing power of provincial landholders, the outbreak of plague (627–628 AD), destruction of industry, infrastructure, and civilian property, along with unprecedented public criticism of economic and social imbalances, were the primary factors that led to the Sassanid Empire's fall and the subsequent Islamic conquest of Iran (Maresca, 2019). The sharp decline in agricultural production led to a reduction in the country's tax revenue. In addition, decreased attention to the country's water infrastructure caused severe floods. In total, the food and economic security of the country was severely endangered. The Sassanids declined like a living creature that decays at the end of its life.

Immediately after the arrival of Islam, Iran had a messy and disorganized environment. Muslims tried to change the country's religious, political, institutional, and social structure. The implementation of Islamic customs[132] and laws[133-134] was a significant step toward the Islamization of society. In the meantime, water could be an essential link between custom, religion, law, and community, but there were obstacles in the Muslims' path. In the sharia sources, there were only some concepts, such as justice, fairness, and balance, for the benefit of all societies (Naff, 2009). Although the Quran[135] has 63 references to water (Farshad and Zinck, 1998), it does not assert any clear duty or rule on water supply and consumption (Absar, 2013). The lack or insufficiency of fundamental rights and obligations regarding access to water, sanitation, sharing, and selling water was the main barrier to the Islamization of water-related rules. It should be noted, however, that neither the conquest of Iran by the

Table 3 A list showing some of the existing watermill heritage sites in Iran.

Province	City
East Azerbaijan	Jolfa
Bushehr	Dashtestan, Dashti, Deyr, Asaluyeh, Kangan
Chaharmahal and Bakhtiari	Shahr-e Kord, Koohrang
Fars	Sarvestan, Jahrom, Eqlid, Estahban, Darab, Nayriz, Bavanat, Larestan, Qir and Karzin, Khorrambid, Lamerd, Kazerun, Fasa, Firuzabad, Zarrin Dasht, Mamasani, Shiraz, Marvdasht, Sepidan, Pasargad, Mohr.
Gilan	Siahkal
Hamadan	Malayer
Hormozgan	Hajji Abad, Bastak
Ilam	Ilam, Chardavol, Dareh Shahr, Deh Luran
Isfahan	Aran va Bidgol, Ardestan, Isfahan, Meymeh, Khansar, Kashan, Mobarakeh, Nain, Najafabad, Tiran and Karvan, Natanz
Kerman	Kerman, Rigan, Kouhbanan, Zarand
Kermanshah	Dalahu, Kermanshah, Kangavar, Gilan-e Gharb,
South Khorasan	Ferdows, Birjand, Boshruyeh, Tabas, Nehbandan, Zirkuh
Khorasan Razavi	Mashad, Taybad, Khaf, Kashmar, Gonabad, Nishapur, Bajestan, Sabzevar
North Khorasan	Bojnurd, Jajarm, Maneh-Samalqan
Khuzestan	Dezful, Shushtar, Andimeshk, Behbahan
Kohgiluyeh and Boyer-Ahmad	Dena, Boyer-Ahmad (Yasuj), Gachsaran
Lorestan	Khorramabad, Aligudarz, Dorud, Kuhdasht, Azna
Kurdistan	Bijar, Saqqez, Diwandareh, Qorveh
Markazi	Zarandieh, Saveh, Mahalat, Arak, Khomein
Mazandaran	Behshahr, Do-Dangeh
Qazvin	Buin-Zahra, Qazvin
Zanjan	Khodabandeh (Deh Shir)
Tehran	Robat Karim, Tehran, Shahr-e-Rey
Yazd	Yazd, Mehriz, Meybod, Ashkezar, Ardakan, Bafq, Meybod
Sistan and Baluchestan	Zabol, Zahedan, Khash

Muslims nor the process of Islamization of the Iranian people occurred suddenly; both sides could adjust to the new circumstances.

There were some contradictions between Islamic rules and traditional customs in some cases. In the Islamic view, water, land, and crops are indivisible, interrelated, and interdependent properties. According to the precepts of sharia, water cannot be possessed by anyone; it is a free substance, and beyond private ownership, no cost ought to be determined to use it, and it cannot be sold. Riparian water rights for allocating water have commonly been limited to adequate amounts for a particular crop area (Naff, 2009). Such a condition was in stark contrast to the Sassanid system. The Sassanid Empire had a rigid social stratification in which social classes differed in dignity, rank, right, ownership, and control of sources, wealth, and social activities (Aarab, 2016). In this system, nobles and priests lived in a luxurious form, incomparable to a farmer's life. This form was utterly different from Islam, which emphasized justice, equality, and fairness. To establish an Islamic system, great flexibility was needed to reach a compromise with Iranians. At the time, Muslim jurists had to ignore their laws or make slight changes in former Iranian laws (Wilkinson, 1990).

Although agriculture remained the base of the economy and society in the Early Islamic period, agricultural and water infrastructure investment declined until the beginning of the construction period. The differentiation between Muslims and non-Muslims[136], the destruction and abandonment of water infrastructure during wars[137], the disintegration of the administrative structures, and changes in rules and regulations were the main reasons for the weakening of agriculture in the age of transition (Soroush, 2014; Daniel, 2019). However, immediately after strengthening Islam's foundations in Iran, the Muslim rulers focused on developing the agricultural sector to stabilize the economy. In this period, some older structures were being renovated, water infrastructures were being updated, and rural settlements were being expanded (Neely, 1974; Watson, 1983). Similar expansions have been observed in the United Arab Emirates (al-Tikriti, 2011), Jordan (Mango, 2010), Iraq, and Syria (Rousset, 2010). Some of the qanats in the Arabian Plate seem to dig for the settlement of the foreign Persian population following the Muslim conquest of Persia (Morony, 2002; Ulrich, 2011), where the survival of new Muslims without qanat systems must have been tough. It was common for qanats to be connected to pools[138] of different sizes and shapes, which served as storage facilities for washing rituals[139] prior to prayer (Genequand, 2012). According to al-Tikriti (2011), these qanats were generally dug or revived with deep mother-wells to access the lowering groundwater table. In 2018, Avni expressed that further research is necessary to determine whether groundwater drawdowns are due to aquifer over-drafts from the Sassanid era or climate change. The structure of the qanats, however, led Avni (2018) to suggest that the Late Sassanid period and Early Islamic periods can be examples of the second stage of qanat evolution, as proposed by Boucharlat in 2017. However, the strong possibility is that numerous settlements were founded during the Islamic period due to the disappearance of previous communities following the Muslim conquest.

Water in the Islamic Golden Age. In a long period between the eighth to the end of the twelfth century[140], the Muslim world underwent a golden age of advancement in science, agriculture, economy, art, architecture, and literature (Petersen, 1996). During the eighth century, paper replaced parchment as the primary writing material for administrative uses. The advent of paper made it easier for Islamic scholars to write, share, and spread manuscripts (Petersen, 1996). The opening of the House of Wisdom in Baghdad coincided with a growth in scientific collaboration between Muslims and Greek, Roman, Chinese, and Hindu scholars[141]. At that time, water-related sciences were among the most attractive fields for Iranian scientists. Numerous documentary and archeological records show the efforts of elites in the Samanid Empire (819–999 AD), Buyid Dynasty (934–1062

AD), Ghaznavid Empire (962–1186 AD), and Seljuk Empire (1016–1153 AD) to solve water-related problems (Savory, 2007; Bastanirad, 2012). The oldest textbook on hydrology and hydrogeology is a book entitled "*The Extraction of Hidden Waters*," written by the Iranian mathematician and engineer "Abubakr Mohammad Karaji" (935–1029 AD), as late as ~1000 years ago[142] (Ataie-Ashtiani and Simmons, 2020). In this book, the author addresses different types and origins of water, exploring groundwater in drylands, approximating the groundwater depth, digging wells, constructing qanats, estimating the protection area around qanats, water-related laws, field investigations, and instrumental innovations.

In 1014 AD, Avicenna[143], the brilliant Iranian scientist, in his book titled "The Canon of Medicine"[144], further provided some explanations about the quality of water and the distribution of diseases by water and soil. Nearly at the same time, another Iranian scientist named "Abu Raihan Muhammad al-Biruni" (973–1048 AD), in his books entitled "*The Remaining Signs of Past Centuries*"[145]; "*Alberuni's India*[146]"; "*A Critical Study of What India Says, Whether Accepted by Reason or Refused*"; and the "*Mas'udi Law*," provided some fundamental explanations on various bodies of water and the artesian water (Yousif, 2000).

New water infrastructures were built during the period, and old ones were reconstructed. Among the small dams and bands that were made in this period, the Buyid dams of "Qur'an Gate,"[147] "Band-e Air," "the Ghaznavid dams of "Feiz Abad" and "Tous"[148], and the Ilkhanate dam of "Kebar"[149] can be mentioned (Tanchev, 2014; Norouz and Noorzad, 2015). Besides, qanat's technology expanded to more than 34 countries under different names (Behnia, 2000; Habashiani, 2011) (Table 4). Despite all efforts made during this period, the lack of creativity and investment in promoting water-related infrastructure and technologies, wars and territorial conflicts, prioritizing economic and political concerns over social benefits, and poor water governance have resulted in water insecurity over centuries.

Discussion and conclusions

The management, governance, and development of water resources in Iran have always been fraught with ups and downs, affecting Iranians' economic power, social evolution, cultural values, religious beliefs, administrative practices, legal decisions, and political paradigms in either a positive or a negative manner. Even though Iranians place a high priority on water and its importance is well documented, relatively little attention has been paid to the historical interrelationship between man and water from different management, technological, and cultural perspectives. This study allows us to evaluate our past failures and successes, giving us insight into how we should proceed in the future. This study shows most Iranian governments repeated the past without learning from it. It was only the strong empires of the Achaemenids and Sassanids that were able to stimulate the Iranians to innovate and improve their water technologies, rules, and management practices. For instance, a major focus of the Iranians during the Islamic Golden Age was the theoretical development of science; as time went on, they failed to water-related problems practically. Water-related problems have been piling up over the years and there has been no motivation to find a solution to them in any meaningful way.

The loss of ancient water technologies was also caused by the forgetfulness of the past, which allowed non-native alternatives to take their place. The elimination of these technologies, then, led to the elimination of their scientific and technological culture. As today's users became familiar with modern water technologies, they paid attention only to the positive side of modernization without considering what to do about the negative impacts. Among the many examples of vanishing technologies, the qanat is one of the most obvious. Indeed, the role of qanat in supplying water declined due to the Iranians failure to reduce its systemic disadvantages. As agriculture and related sectors have grown, the qanat system has not competed with deep-pumped wells for water supply. In comparison to qanats, deep-pumped wells are more private for agricultural activities, have more power to extract, are cheaper to maintain, and are easier to run. Despite its advantages, this technology also has had some disadvantages. Uncontrolled use of deep wells, poor recharge, and unsustainable management have caused many difficulties for water-related sectors. The full extent, however, is unknown but rising conflicts over water, loss of cohesion among local residents, agricultural losses, water quality deterioration, wells and springs drying up, declining effluent flow, increasing soil-water salinity, rising pumping costs, occurring land subsidence, and ecological degradation are among the most critical challenges associated with groundwater depletion (Mohammadi Arasteh and Shoaei, 2020; Golian et al., 2021). The notable point is that the change in water-related technology itself is not a significance challenge, whereas how this change affects our culture and society is an equally significant consideration.

According to this study, many of the Iranians' water-related problems can be traced to the climatic and geographical characteristics of the country. Iran, with an arid- and semi-arid climate, is characterized by fragmented geological blocks, irregular spatial-temporal distribution of water resources, and highly variable topography and climate. The characteristics of Iran's climate (e.g., the intensity, duration, and distribution of rainfall, temperatures), geography, and topography of the land as well as soil fertility, play a significant role in determining the quality, quantity, and hazards associated with water. In turn, these parameters contribute to the complexity of society and the relationship between humans and water. As a result of the unbalanced distribution of water, Iran's settlement patterns (e.g., density, size, and distance from water resources) have always followed pattern of water resources in time and space. The emergence of the first agricultural societies in northern Iran, with a much faster growth rate in eastern areas, indicates how geoclimatic factors control settlement patterns. This trend is prevailing in today's Iran, so the west and north of Iran are relatively more developed than the center and east.

Table 4 The historical spread of qanat under different names (in parentheses).

Continent	Country
Asia	Iraq (Qanat), Bahrain, Oman, United Arab Emirates, Saudi Arabia, Palestine, Jordan (dhwawi), Oman (Falaj for single and Aflaj for plural), Syria (Qanat Romani), Yeman (Felledj, Ghayl, Miyan), Afghanistan (Kariz, Kahrez), Pakistan (Kariz or Kahn in Balochi), China (Karez, Kan'erjing), Japan (Mambo, Mappo), Korea (Ma-nan-po), Kazakhstan, Azerbaijan (Su lağımı), India (Karez, Nahars, Kundi-Bhandara, Surangam), Mongolia, and Armenia (Kahreze)
Africa	Libya (Fughara,), Algeria (Foggara), Egypt, Tunis, and Morocco (Khattara, and Rhettara)
Europe	Cyprus, Greece, England, France, Germany, Nederland, Spain (Galerias, Paquio, Galerías, Mina de aquaor viajes de agua), Canary Islands (Galerias, Paquio), Italy (Ingruttato for single and Ingruttati for plural), Croatia (Kanata), and Russia
South America	Chile, Mexico, Peru (Puquios), and Brazil (Galerias, Paquio)

The lack of interaction between locals and their governments separates today's water resource management from that of the Achaemenids and Sassanids. The Achaemenid and Sassanid governments were aware of the importance of enlisting the support and participation of all societies in managing water. Thus, different communities could contribute significantly to strengthening and improving water governance. These governments must provide the necessary political, administrative, and economic resources, as well as the willingness to implement these changes. Regarding fundamental changes in water sectors, water resource development in the Achaemenid and Sassanid periods should be explored beyond words related to water. In the wake of improvements in institutions, laws, public affairs, and communications, both empires constituted a powerful statement of unity, cooperation, and support among people. At the same time, they developed their water resources using the latest technology and management skills, which resulted in improved agricultural productivity. An increase in agriculture production meant food security, trade development, and an increase in tax collection. Improvement of previous components caused population growth, urban development, political stability, territorial expansion, and cultural adaptations. In this way, the Achaemenids could connect the different rings of a chain and form the largest empire in the world.

In present-day Iran, a significant challenge is that water resource development is central to most "top-down" or government-led processes, ignoring local water management concerns. Even though government regulations contribute to the development of water resources, they are insufficient in meeting all the needs. Generally, government-based programs are too broad in scope and application to consider the diversity and unique needs of the people in a given locality. Additionally, present-day government relies extensively upon scientific, technological, and expert capabilities, overshadowing local, traditional, and indigenous approaches to address water-related issues. Such conditions prevent the government from accessing public opinions, experiences, perceptions, expectations, solutions, and feedback. They sometimes hinder locals from being informed of the goals and other necessary details for applying major water-related plans, interpreting the situation as a "single-actor play on stage". Ignoring local power could become a source of tension and conflict between states, sectors, and communities, particularly in matters relating to water allocation. Iran's water sectors will need considering "bottom-up" approaches, emphasizing culture, territory, local diversity, and social accountability.

Regarding population growth, urbanization, and food consumption, today's Iran is more or less comparable to the Sassanid Era. However, there is a significant difference between the water administrations of the Sassanid period and those of the modern Iranian period. "Diwan-e Kastfezoud" governed Sassanid water affairs, whereas water issues now fall under the Department of Environment, the Ministry of Energy, the Ministry of Agricultural Jihad, and the Ministry of Health and Medical Education. Another problem is that the water resources of Iran are managed by political boundaries rather than natural ones. It is not unusual for several provinces or ministries to be responsible for managing a catchment or an aquifer. Ultimately, this results in confusion and wasting time, effort, and resources.

Wars and territorial conflicts, both between and within nations, have been recurring challenges in the past and the present. During wartime, the entire country's sectors receive less attention, causing a mess and destabilization. Among direct and indirect consequences of war are: (i) soil and water degradation; (ii) increasing water allocation conflicts; (iii) threatening public health; (iv) agricultural losses; (v) decreasing rural family incomes; (vi) decrease in agricultural tax, and (vii) forced migration. Over the last century, Iran was embroiled in two prolonged civil wars: Iran's Anglo-Soviet invasion (1941) and the Iran-Iraq War (1980–1988). The eight-year Iran-Iraq War was similar in location to the Arab-Sassanid War. During these wars, most water-related systems in southwestern and western Iran were ruined, damaged, or polluted, creating a chaotic environment for developing water resources.

From a social point of view, cultural factors have significantly influenced the development of water resources in Iran. The culture of Iranians, locally or regionally, significantly shapes their attitudes, values, and behaviors toward the water. Iran's lifestyle, traditions, and beliefs are in some way connected to water, which symbolizes life, purity, renewal, and reconciliation. The way in which water is used, saved, protected, and respected represents a significant part of the country's cultural identity. Despite having rich water-related customs, present-day Iranians have moved away from their past. However, in some villages or cities (e.g., Yazd, Sabzevar[150], Golpayegan[151], Arak[152], Larijan[153], and Gonabad) some traditional water-related customs and festivals are followed. Water-related values and traditions, however, should be examined historically to gain insight into how the practices of these cultures can sustain water resources.

There are many other sobering lessons to learn. In ancient Iran, water-related problems were solved by fundamental concepts of hydraulics. In the same way, water-related infrastructures were built using locally available materials. Still, these managing practices and technology constituted the necessary foundations for today's water governance. However, although water rights, fairwater allocation, pricing plan, sustainable use, public service, social responsibility, quality criteria, social benefits, use efficiency, water integrity, and water governance have been highly regarded in modern sciences, combining these concepts with the traditional ones makes them more efficient. Accordingly, restoration, stabilization, and upgrading of outdated infrastructures and techniques are necessary before they become forgotten.

Data availability

In the present study, no datasets were generated or analyzed, so no data sharing policy applies.

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Notes

1 Approximately 130 of these documents are cited in this article.
2 "Irān," meaning "land of the Aryans," has undergone many changes in its areas. Modern Iran occupies a prominent place in the Iranian Plateau and its bordering regions, where the Iranian culture has been greatly influenced. Former Iran includes much of the Caucasus, Iraq, Afghanistan, Pakistan, and Central Asia. Among other names for Iran in literature are "Iranweij," "Eran-Shahr," "Pars Region," "Greater Iran," "Persia," and "Iran-Zamin." See *Gershevitch I (ed.) (1985) The Cambridge History of Iran. Cambridge University Press, UK.*"
3 By area, Iran ranks 18th in the world.
4 The world's average rainfall, is about 860 mm/yr.
5 These masses are characterized by sunny weather, calm winds, and very little rainfall. See *Heydarizad M, Raeisi E, Sori R, Gimeno L (2018) The identification of Iran's moisture sources using a Lagrangian particle dispersion model. Atmosphere 9(10): 408.*
6 These air masses enter Iran from the west, affecting the west and north. After crossing the Alborz and Zagros mountains, their moisture is lost as the temperature rises, resulting in deserts in Central Iran, (*ibid*).
7 Northeast Africa forms these masses, which enter Iran from the southwest. By absorbing moisture through the Persian Gulf, they affect most of Iran, (*ibid*).
8 Also called Kermashahan, Kermanshah is the capital of Kermanshah Province.
9 Khorramabad is the capital of Lorestan.

10 Kashaf-rud is the main river of Khorasan Razavi Province.
11 In Persian, "Rud" means "River."
12 This Lower Paleolithic site is located along the Sefid-Rud River in Rostam Abad, Gilan Province.
13 Tape Chahar Boneh is a Late Neolithic site located on the Qazvin Plain in central Iran. See *Pollard AM, Davoudi H, Mostafapour I, Valipour HR, Fazeli Nashli H (2012) A New radiocarbon chronology for the late Neolithic to Iron Age in the Qazvin plain, Iran. The International Journal of Humanities, 19(3):110–151*.
14 The Neolithic site of Chogha Bonut lies on the Susiana Plain in southwestern Iran. Site evidence demonstrates prehistoric settlements and early social development before the invention of pottery in the eighth millennium BC. See *Darabi H, Bangsgaard P, Arranz-Otaegui A, Ahadi G, Olsen J (2021) Early Neolithic occupation of the lowlands of southwestern Iran: new evidence from Tapeh Mahtaj. Antiquity, 95(379):27–44*.
15 Ali Kosh was one of the first agricultural communities in the Zagros Mountains, Ilam Province, western Iran. *For more details see Hole F (2004) Neolithic age in Iran. Encyclopedia Iranica*. https://referenceworks.brillonline.com/entries/encyclopaedia-iranica-online/neolithic-age-in-iran.
16 The Pre-Pottery Neolithic site of Ganj Dareh lies in the central Zagros Mountains of Kermanshah Province, west of Iran.
17 "Tape" or "Tappe" is an abbreviation for "Tappeh," which is Persian for "Mound" or "Tell".
18 "Tape Pardis" is an ancient agricultural community near Jajrud, Tehran Province.
19 "Cheshmeh Ali" is a Late Neolithic site on the Tehran Plain.
20 The Sialk Archeological Complex is located in Kashan, Isfahan Province.
21 Early Neolithic settlement, Tape Zagheh (Tappeh Sang-e Chakhmaq) is situated in the southern part of the Qazvin Plain (Buin-Zahra).
22 It is one of the oldest human settlements in Harsin County on the Mahidasht Plain in South Zagros.
23 The Iranians had kept goats and sheep since ~10,000 years ago. Cattle were domesticated ~8000 years ago, much earlier than horses. Detailed information can be found in *Zeder MA (2008) Animal domestication in the Zagros: an update and directions for future research. MOM Publications, France*.
24 The Jiroft Complex is a collection of archeological sites in Kerman Province.
25 "Shahr-i Sokhta", "Shahr-e Sukhteh" or "the Burnt City," is the remnant of an ancient city government in Sistan and Baluchestan Province.
26 "Tape Yahya" is an archaeological site in Kerman Province.
27 "Tape Hissar" is a prehistoric site located south of Damghan in Semnan Province, Northeast Iran.
28 "Tape Ghabrestan" is a Chalcolithic site in the Qazvin Plain.
29 "Mafin Abad" is a Chalcolithic archaeological site in the west of Tehran.
30 "Shahr-e Rey" is the capital of Rey County in Tehran Province.
31 By discharge and length, "Karun" is the largest river in Iran. It has an average discharge of 575 m^3/s and a length of 950 km[141].
32 With 755 kilometers, "Karkheh" rises in the Zagros Mountains of western Iran and passes west of Shush (ancient Susa) in Khuzestan Province. It fed into the Tigris River near Iran-Iraq's border in ancient times, See *Afshin Y (1994) Rivers of Iran. Jamab Consulting Engineers Company, Ministry of Energy, Tehran, Iran*.
33 Flowing in the provinces of Khuzestan and Kohgiluyeh and Boyer-Ahmad, the Jarrahi River is one of the major rivers in southwestern Iran. Having a length of 438 km, it is the 11th longest river in Iran (*ibid.*).
34 With 44 kilometers, "Shavur" or "Shavoor" is one of the perennial rivers in the Susiana Plain (*ibid.*).
35 "Dez" is the principal tributary of the Karun River and measures about 400 km in length (*ibid.*).
36 A sealed tank for collecting and temporarily storing sewage.
37 Hammurabi's Code was inscribed in the Akkadian language on a diorite stele 2.25 m tall with a circumference is 165 cm at the summit and 190 cm at the base. The Code's 282 numbered paragraphs are not ordered. Scheil (1902) speculated that the stele has been transported to Susa by the Elamite King Shutruk-Nakhunte. The tablet is on display at the Louvre in Paris. See *Scheil, JV (1902) Memoirs of the Delegation in Persia. Ernest Leroux, Paris, France*.
38 In Hammurabi's Code, articles 53 to 56 deal with irrigation, while articles 241 to 283 deal with agriculture. More information at *Roth MT (1995). Mesopotamian legal traditions and the laws of Hammurabi. Chicago-Kent Law Review 71:13–39*.
39 Present-day Hamadan.
40 The first dynastic capital and final resting place of Cyrus the Great (550–530 BC).
41 The Achaemenids' ceremonial capital during the Darius the Great Reign (522–486 BC). Other names are "Pârsa" or "Pârseh" in ancient Persian, "Takht-e Jamshid" in modern Persian.
42 It is comprised of a smaller plain named "Pasargadae Plain."
43 The festival, known as "Nowrouz," (a new day), marks the arrival of spring on the March equinox, usually on March 21.
44 Also known as "Polvar," "Parvab," "Balaghi River", and "Sivand."
45 In Persia: "Pole-Khan."
46 Also known as "Doroodzan Dam."
47 Some parts of the Didegan Dam body remain sufficient to guess its original dimensions and materials.
48 This fastening tool is called "Dom Chelcheleh" (Swallow-tail).
49 The "Qanat" term is extracted from the Arabic "Qanāh," meaning tube and channel (reef). The word is related to Hebrew "Qāne" and Akkadian "Qanû" with a Semitic (Syro-Arabian languages) root.
50 In Persian: "Rahrow", Dehleez", or "Kooreh."
51 A traditional water-resistant mortar made of clay and lime mixed in a six-to-four ratio. In some cases, the mixture may contain sand, Typha fibers, goat hair, straw, and ashes in specific proportions).
52 In Persian: "Muqanni."
53 In Persian "Madar chah."
54 Located in the Khorasan province of eastern Iran, Gonabad is home to the deepest active mother-well in the arid regions of the country, measuring ~270 meters deep. See *Papoli Yazdi MH, Labbaf Khaneiki ML (2000) The role of Qanat in the formation of civilizations; sustainability of Qanat civilization and culture. In Proceedings of the international conference on Qanat (Vol. 1), Yazd Regional Water Authority, Yazd, Iran*.
55 In Persian: "Mazhar."
56 In Pesian: "Milleh."
57 A traditional water reservoir, the Ab-Anbar is covered by a dome-like roof and equipped with several ducts. It was typically dug fully or partly below ground level to store water in cities, villages, forts, caravans, and routes in pre-modern Iran.
58 Yakhchal is a domed-shape subterranean structure used for ice making and storing where, during the winter, qanat water was converted to ice, cut out, and stored in deep pits beneath the stepped, domed ice houses.
59 Antiochus was a Greek Hellenistic king who ruled the Seleucid Empire between 175 BC and 164 BC.
60 He describes how Arsaces sought to destroy the qanats and thus cut off the water supply to halt Antiochus' advance towards Qumis, the lost Parthian capital.
61 These records show Sargon II discerned that the defeated city had vibrant and varied vegetation while there was no river to cross. Therefore, he tried to realize why the region could stay green and lush. The answer to this question lay in the existence of qanats. The qanat construction was on "Ursa" orders, the king of the area, who had rescued the people from thirst and turned Uhlu into a prosperous and green land, See *Goblot H (1979) Qanats: a technique for acquiring water. Mouton Editions. Paris, France. pp: 231*.
62 The king of the Neo-Assyrian Empire (722–705 BC).
63 An Assyrian name, used for people who live in Eastern Turkey, Armenia, and Western Iran.
64 In the Kerman Province of southeastern Iran.
65 In Persian: "Harim."
66 In Persian: "Mogh."
67 The truth behind this is that farmers had given a part of their production and income to priests in first-fruits offerings, donations, and gifts, mostly at harvest time.
68 Satraps were the governors of the provinces of the Achaemenids.
69 It was under the control of the Seleucids, but Parthia's Seleucid governor proclaimed his independence. More information is available in *Brosius M (2006) The Persians. Routledge (Taylor and Francis). Abingdon, UK*.
70 Polybius, a Greek historian of the Hellenistic period, recorded that Arsaces III, one of the Parthian kings, tried to destroy some qanats and interrupt water flow to make it difficult for Seleucids to advance toward the Parthian capital, (*ibid.*).
71 Improved transportation, well-developed coinage systems, and the opening of the Silk Road played a significant role in trade development in this period.
72 It means "the Bureau of Water Consumption and Production."
73 It means "Book of a Thousand Judgments." This book is a compilation of the social, moral, civil, and criminal laws of the late Sasanian period, written in the Pahlavi language. See *Daryaee T, Rezakhani K (2016) From Oxus to Euphrates: The world of late antique Iran. H&S Media, London, UK*.
74 An increase in the number of coins, pottery, and ceramic samples, a change in settlement configuration, size, and density, and a survey of water canals can indicate that the population has grown.
75 A Middle Persian name for Firuzabad City in Fars Province.
76 Bishapur was an ancient city very close to Persepolis.
77 The city of Darabgard (Darab) is among the oldest in the province of Fars.
78 Located in the south of Shushtar City in Khuzestan Province.
79 There are several transcriptions of this word. It is known in Greek as "Paradeisoi", "French as "Paradis", German as Paradies", English as "Paradise", Hebrew as "Pardes", and Arabic as "Ferdows". See https://en.wikipedia.org/wiki/Paradise_garden
80 The Nahrawan Canal was built by the Sassanids to transport water from the Tigris to the Diyalah River for agriculture.
81 In Persian: "Ab-Salar."
82 In Persian: "Dabir."

83 In the Sasanian and early Islamic period, the term "Dehqân" was used for minor landowners directly involved in agriculture, who was the manager of local affairs on the village scale, and whom peasants were forced to obey. Later, the term "Kadkhoda" replaced this word. In 1976, the Kadkhoda position was withdrawn from Iran's administrative structure and replaced by the "Village Council." See *Spuler B (2014) Iran in the early Islamic period: politics, culture, administration, and public life between the Arab and the Seljuk conquests, Iran Studies, 12:633–1055*.
84 In Persian: "Ab-Ban" or "O' ban."
85 In Persian: "Kayyal" or "O' yar."
86 In Persian: "Raieyat."
87 The other Sacred Fires were "Adur Farnbag" and "Adur Gushnasp," which were associated with the priest and warrior classes, respectively.
88 This Sacred Fire is referenced as "Azar Barzin Mehr."
89 Based on Zoroastrian religious traditions, farmers will be wiser, more affluent, and cleaner in agricultural work with the help of this fire.
90 Manichaeism was a fast spreading in the Sasanian Empire founded by an Iranian named "Mani" in the third century (216–274 AD). See the following link for more information *Rezakhani K (2015) Mazdakism, Manichaeism, and Zoroastrianism: In search of orthodoxy and heterodoxy in late antique Iran. Iranian Studies, 48(1):55–70*.
91 Mazdakism was a dualistic religion that rose in Iran as an offshoot of Zoroastrianism, (*ibid*.).
92 In Persian, the" weir" term is called "Band." The main difference between the Sassanid's weir and today's dam is that a weir allows water to pass, but a dam does not. Hence, a weir can be used for increasing water level, not water storage purposes.
93 Shushtar is located in Khuzestan Province. "Sostrate" and "Tustar" are the ancient names of this city.
94 Dezful is located in Khuzestan Province.
95 At this time, the Khuzestan plains, due to their large wheat, barley, oil-seeds fields, and citrus fruits growing, were considered the breadbasket of the Sassanid Empire. The 1700 years old weirs and watermills in Dezful and Shushtar were part of the Dez and Karun hydraulic systems. Detailed information can be found in *Wilkinson TJ, Boucharlat R, Ertsen MW, Gillmore G, Kennet D, Magee P, Rezakhani K, De Schacht T (2012) From human niche construction to imperial power: long-term trends in ancient Iranian water systems. Water History 4(2):155–176*.
96 "Caesar's Weir," "Valerian Weir," and "Shadorwan Weir-bridge" are other names of "Band-e Kaiser."
97 The width of slices ranges from 1.7 m to 2.85 m. See Roshani Nia A, Zalaghi F, Sallakhpur M (2007) Investigating of Water Diversion Structures and Irrigation Network in Ancient Time of Shushtar City, Typical Study of Dam, Bridge-Dam, and Creek. In: Proceedings of the International History Seminar on Irrigation and Drainage: 501–513. Iranian National Committee on Irrigation and Drainage. Tehran, Iran.
98 During 1632 and 1669, Band-e Kaiser and Band-e Gargar were restored by the Safavid governor of Shushtar and Dezful named "Vakhushti Khan Gorji." His son, named "Fathali Khan," who ruled these areas from 1669 until 1694, repaired Band-e Kaiser, but apparently, he made a great mistake. He decided to decrease the Shoteit River discharge by making holes and cracks in the Mizan weir's gates. He thought the workers could get rid of water and repair the Kaiser Weir effortlessly. This action increased the discharge of the Gargar River. After decreasing the Shoteit discharge, the farmlands on both sides of this river gradually became dry and unproductive, bringing many negative social and economic consequences for Shushtar and Dezful, (*ibid*.).
99 In the eighteenth century, the Mizan and Kaiser weirs, especially their mills, were damaged by a flash flood, causing heavy losses to the economic and social conditions of Shushtar. To solve related problems, these weirs were repaired for three years from 1806 to 1809 by "Mohammadali Mirza Dolat Shah," an Iranian prince of the Qajar Dynasty. Detailed information can be found in *UNESCO (2008) World Heritage Convention Nomination of Properties for Inclusion on the World Heritage List, Shushtar historical hydraulic system, report, Paris, France*.
100 In Persian: "Asiyab."
101 On a small scale (e.g., household level), this process was done by human muscle power.
102 Windmills extensively appeared in eastern Iran with a dry climate between 500 and 900 AD. For more information, see *Sharma R (2009) Future Power, Future Energy: Wind Power. The Energy and Resources Institute (TERI). New Delhi, India*.
103 Wheat, barley, oilseeds, corn, occasionally turmeric, and sugarcane.
104 "Shapur I" was the second Sasanian King of Kings of Iran who ruled from 240 to 270 AD.
105 "Shapur II" was the tenth Sasanian King from 309 to 379 AD.
106 "Kavad I" was the Sasanian King of Kings of Iran from 488 to 531 AD.
107 "Khosrow I," also known as "Anushirvan," was the Sasanian King of Kings of Iran from 531 to 579 AD.
108 The water tower diameter differs from a thin 66 cm at the "Estahban" watermill in Fars Province to a wide of 3 m at Shushtar*Harverson M (1993) Watermills in Iran. British Institute of Persian Studies-Iran 31(1):149–177*.
109 The nozzle's greater diameter causes a more significant discharge toward the wheel and less time to feed the water tower.
110 Also known as "Runner Stone."
111 Known as "Eye."
112 Millstones in qanats, compared to river mills, were remarkably small in diameter.
113 There are a few disagreements about the horizontal watermill's efficiency. For instance, Wikander (2000) judged the Greek watermill technology to be approximately as efficient as the Roman ones, whereas Forbes (1958) stated that the Greek watermills were less efficient. See *Wikander Ö (2000) Handbook of ancient water technology. Brill, Netherlands; Forbes RJ (1958) Studies in ancient technology. Industrial arts, USA. pp: 268*. See *UNESCO (2008) World Heritage Convention Nomination of Properties for Inclusion on the World Heritage List, Shushtar historical hydraulic system, report, Paris, France*.
114 The site is Iran's 10th cultural heritage site, registered on the UNESCO World Heritage list.
115 The watermill complex is called "Sika."
116 The Deh-Luran Plain is located in Ilam Province, southwestern Iran, near the Iran-Iraq border.
117 Jiroft is a city in Kerman Province, south-central Iran.
118 Nishapur or Nishabur is a city in Khorasan Razavi Province, in northeastern Iran.
119 Located in Yazd Province.
120 Located in Esfahan Province.
121 Located in Fars Province.
122 Located in Esfahan Province.
123 Located in Yazd Province.
124 Located in Yazd Province.
125 Kerman is the capital city of Kerman Province.
126 These mills were important for qanat owners because some of the rental income from watermill leases had been spent on qanat's care.
127 "Zayandeh-rud" is the largest river on the Iranian Plateau in central Iran.
128 In this mill, the wheel's bottom is submerged in flowing water, where there are no head differences.
129 In some parts of Dezful, these are locally known as "Louvineh."
130 The "Sassanid Bridge" is located in the old part of the city known as the "Qaleh" (the Castle) Neighborhood.
131 Following Aarab (2016), Muslim forces first attacked southern Iraq and the plains of Khuzestan, which were the political and economic heartland of the Sassanid state. See *Aarab AA (2016) Survey of Iran's social structure in the transition from the Sassanid to the early Islamic era from the manuscript and archaeological evidence. Cedrus 4:341–352*.
132 In Arabic, called "Urf."
133 In Islam, the principles and rules set based on clear and definite texts of the Quran are scant; sharia instead supports common virtuous regulations. It contains several directions expressed in the Quran, augmented through the Sunni (an extensive collection of the Prophet Muhammad's ideas, thoughts, beliefs, morals, manners, and learning-teaching; validated by sayings of the Prophet (called "Hadith"), a unanimous agreement among scholars and religious figures regarding a religious ruling (called "Ijma"), and logical reasoning by analogy (called Qiyas). 'Suitable' local customs (Urf) are identified as background resources of law. Following Muhammad's death in 632 AD, the Sharia laws became mature along with the expanding Muslim Empire until it reached its full development during the Abbasid Caliphate (750–1258). Most Islamic communities no longer consider "Ijtihad" (independent reasoning) as a valid mode of legal inquiry, while the Shiite tradition has always accepted "Ijtihad" as a source of law. More information can be found Al-Awa M (1973) The place of custom in Islamic legal theory. Islamic Quarterly17:177–179.
134 Also known as "Sharia," "Shariah," or "Shari'a."
135 The Quran is also Romanized as the "Qur'an" or "Koran."
136 Although Arab Muslims allowed farmers to own their land, qanat, and well, they divided the Iranians into Muslims and non-Muslims. Muslims had to pay taxes. Non-Muslims kept their legal system, but they had to pay "Jizyah" in addition to taxes. For this reason, many non-Muslim Iranians were forced to leave their lands and migrate to neighboring regions such as India, See *Faruqui NI, Biswas AK, Bino MJ (2001) Water management in Islam. United Nations University Press, Japan*.
137 One difficulty was the decline of irrigation agriculture throughout the "Dark Ages of the Sasanians," which resulted in flash floods, which washed away croplands, damaged water infrastructure, and threatened food security, safety, and the economy of the territory.
138 In Persian "Hoze."
139 Islam refers to it as "Wudu."
140 This period in Iran started with the rise of the Samanids. It ends with the fall of the Khwarazmians and the Mongols' arrival (1098–1219 AD).

141 During the Abbasid caliph Harun al-Rashid (786–809 AD), the Islamic government strongly patronized scholars. After the foundation of the House of Wisdom (in Arabic Bayt Al Hikma) in Baghdad, scholars from different parts of the world were tasked to collect and translate all of the classical knowledge of the day into Arabic and then Persian and Turkish. Although the Islamic Golden Age began in Baghdad and developed in Islamic regions, it was not just the outcome of Islamic achievements. For details, see *Gutas D (2012) Greek Thought, Arabic Culture: The Graeco-Arabic Translation Movement in Baghdad and Early Abbasaid Society (2nd-4th/5th-10th c.). Routledge, London, UK*.
142 Today, this book is available in French, Italian, and English.
143 Also known as Abu Ali Sina.
144 This book was written in Arabic, the official language, and then translated into different languages.
145 Also known as "Chronology of Ancient Nations" or "Vestiges of the Past."
146 According to Sorkhabi (2017), Biruni, in his book entitled "Alberuni's India." documented a hypothesis about the artesian phenomenon as follows: "*The elevation of the Waterhouse (aquifer) containing hidden water (groundwater) is higher than the elevation of the artesian well to allow water's flowing out. If the elevation of the Waterhouse is high enough, the water could easily flow to the top of the surface*". These ideas confirm that Biruni and other scholars at their level were aware of the concepts applied in advanced geology, hydrology, and hydrogeology. See the following reference for more information *Sorkhabi R (ed.) (2017) Tectonic Evolution, Collision, and Seismicity of Southwest Asia: In Honor of Manuel Berberian's Forty-five Years of Research Contributions (Vol. 525). Geological Society of America, USA; Biruni ARM (~1030 AD) Alberuni's India: An account of the religion, philosophy, literature, geography, chronology, astronomy, customs, laws and astrology of India about AD. 1030, Amir Kabir Publication, Tehran, Iran*.
147 In present-day Shiraz, Fars Province.
148 In present-day Tous in Khorasan Razavi Province.
149 23 km southeast of present-day Qom, the capital of Qom Province.
150 Located in Razavi Khorasan Province, Sabzevar was previously known as Beyhagh.
151 The city of Golpayegan is in Isfahan.
152 Markazi Province's capital is Arak.
153 Larijan is a town in Mazandaran Province

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Author contributions

MS conceived the study, supervised the research, and wrote the paper with all other authors. AR contributed to the study research and design.

Competing interests

The authors declare no competing interests.

Ethical approval

This article draws upon existing literature and secondary sources of information and as per institutional guidelines, ethical approval was not necessary for this study.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

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