Evolution of water wells focusing on Balkan and Asian civilizations

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ABSTRACT

The provision of water has been a major enterprise in human history. Groundwater was one of the first sources since the prehistoric times to cover human needs. Initially, the exploitation of groundwater has been made by shallow wells and later by boreholes. A water well is constructed through excavation in the ground by digging, driving, boring, or drilling to access groundwater in aquifers. Groundwater wells were used in the Helladic world since Neolithic times. Ancient China developed a sophisticated tool for drilling water wells that is similar to modern machines. Qanat, a system of wells, originated in Iran (Persia), but was adopted by other countries. Moreover, the Indus valley civilization had well-constructed wells mainly for drinking purposes. The construction of wells varied according to local conditions, determined by geology, hydrogeology, and morphology, as well as by local tradition. Furthermore, a well was not just a water source but also became a cultural symbol throughout history, related to local religion and custom. The stepwells in India became not only sources of drinking water, but also holy places (sanctuaries) for bathing, meditation and prayer. In the present review, the evolution of wells through the centuries is examined. The study of water well technologies demonstrates their diachronic evolution and, furthermore, reveals that the ancient people had an outstanding engineering knowledge of water exploitation, which is interesting for water engineering and hydrogeologists, even nowadays.

Key words | aquifer, borehole, dug well, qanat, social-cultural aspects, stepwell

INTRODUCTION

The most traditional and relatively simple method of water supply since prehistory, especially in regions with limited available surface water, was drawing it from wells, namely deep holes made in the ground through which water can be lifted. Reports for well construction in ancient times are found in the Book of Genesis, the first book of the Hebrew Bible.
Wells were known since prehistory (Vigoni 2011). In regions with surface water availability the construction of wells was very limited, whereas in South Greece, as in other Mediterranean countries with low surface water availability, the drilling technology and the development of wells is a well known practice since the early Bronze Age or even earlier (Angelakis & Voudouris 2014). They were usually round in cross-section, lined usually with stone, brick or even wood. Several wood lined wells have been found in central Europe, dating back to the Neolithic era and later (Thomas 2003; Tegel et al. 2012). Both digging and constructing wells were skilled crafts that required specialists. There is little evidence of technological advances in well drilling during prehistoric times in the Mediterranean region (Brantly 1961). Well construction in the Near East was accomplished by humans and animals and was aided by hoists and primitive hand tools. Egyptians had developed drilling systems in rocks as early as 5000 BP (Hodge 2000).

A remarkable series of wells with foot hand holes in Kyssonerga, in a region without springs or rivers on the southwest coast of Cyprus, near to Paphos, is dated in aceramic Neolithic, in the late 10th and 9th millennia and seem to be the earliest known wells (Peltenburg et al. 2000). On the other hand, four circular wells in a Neolithic settlement at Schillerokampos of Cyprus were dated in the first half of the 10th millennium BP. Their openings were ranging from 1.00 m to 1.50 m, while their depth reached 4.00–5.00 m. In spite of their early construction, there are access semi-holes on their walls (Peltenburg et al. 2000). At least two wells from the Neolithic period, around 8500 BP, have been discovered in Israel. One is in Atlit, on the northern coast of Israel, and the other one is the Jezreel Valley (Tegel et al. 2012). In the same period (Bronze Age, ca. 4500 BP) a system of wells to tap groundwater was discovered in Spain. These wells of small depth (less than 20 m) were constructed in floodplains of rivers (Benitez de Lugo Enrich & Mejias 2017).

In the area that nowadays is called Greece (Hellas), people obtained water directly from the earth since prehistory. The water demands of the first human settlements, built on hills, were met by springs. When the water needs increased due to the development of agricultural activities, the groundwater exploitation expanded with the construction of wells (Voudouris 2012). Thereafter, wells were usually used in parallel with water transfer projects and urban water works (aqueducts) (Angelakis et al. 2016).

The Roman author, architect and civil engineer of the 1st century BC, Vitruvius, in his multi-volume work entitled ‘De Architectura’ notes: ‘Si autem fontes (non sunt), unde ductiones aquarum faciamus, necesse est puteos fodere… in puteorum autem fossionibus non est contemnenda ratio, sed acuminibus sollicitaque magna naturales rerum rationes considerandae, quod habet multa variae terra in se genera. est enim uti reliquae res ex quattuor principiis composita. et primum est ipsa terrena habetque ex umore aquae fontes, item calores unde etiam sulphur alumen bitumen nascitur, aerisque spiritus inmanes, qui cum graves per intervenia fistulosa terra perveniunt ad fossionem puteorum et ibi homines offendunt fodientes vi naturali vaporis obturant eorum naribus spiritus animales, uti qui non celerius inde effugiunt ibi interemantur.’ That means, ‘…But if there are no springs from which we can construct aqueducts, it is necessary to dig wells. Now in the digging of wells we must not disdain reflection, but must devote much acuteness and skill to the consideration of the natural principles of things, because the earth contains many various substances in itself; for like everything else, it is composed of the four elements. In the first place, it is itself earthy, and of moisture it contains springs of water, also heat, which produces sulphur, alum, and asphalt; and finally, it contains great currents of air…’ (De architectura VIII, 6, 12). Wells construction varies through the centuries from a simple hole in the loose sediments of a river basin to the stepwells of India, the qanats of Iran, and the shadoofs and sakiehs of India. Vitruvius, bearing in mind the danger of the well digging analyses the right way: ‘…hoc autem quibus rationibus caveatur sic erit faciendum. lucerna accensa demittatur, quae si permanerit ardens sine periculo descendetur. sin autem eripietur lumen a vi vaporis, tunc secundum puteum dextra ac sinistra defodiantur aestructurae. ita que-madmodum per nares spiritus ex aestructuris dissipabuntur. Cum haec sic explicata fuerint et ad aquam erit perventum, tunc saepius saeriplastra ne obturetur vena…’/…”To avoid this the following method may be adopted; a lighted lamp must be lowered; if it continue to burn, a man may safely descend, but if the strength of the vapour extinguish it, then to the right and left of the well let air holes be dug, so that as it were through nostrils, the vapour may pass off.
When this is done and we come to water, the well must be lined with a wall, but in such a manner as not to shut out the springs...’ (De architectura VIII, 6, 13).

A large number of wells has been reported throughout antiquity, the Byzantine period, or even post-Byzantine era. Thus, according to Evlyia Celebi, an Ottoman explorer who travelled through the territory of the Ottoman Empire, 3060 wells were registered in the city of Thessaloniki in the 17th century AD (Kaiafa 2008). Initially, the focus was on identifying artesian aquifers, due to a lack of water pumping technology. If such an artesian (confined) aquifer is drilled by a well, water flows onto the ground surface under natural pressure without pumping. The best known artesian wells were drilled in the wider area of the town of Artois (northern France) during the Middle Ages (Angelakis et al. 2012, 2013).

Dug shallow wells were used in qanat technology, mainly applied in ancient Persia (nowadays is called Iran). Qanats or kariz, which mean a chain of wells, are a most remarkable technology of water supply. Each qanat made up of a series of wells linked in the bottom by tunnel, which collected water from alluvial deposits and soft sedimentary rocks. They are gently sloping, artificially constructed underground galleries, which bring by gravity groundwater from the mountainous area to the lowlands where water is needed, sometimes many kilometers away. At the highest point of the area the first (mother) well is constructed in order to find out the presence of groundwater, and then vertical wells are dug at a distance of 10–30 m, for the removal of soil and ventilation of the tunnel. Much of the population of Iran and other arid countries depended upon the water from qanats (Voudouris et al. 2015).

The history of water use in the Indian valley follows the history of human use and habitation. Indus civilization flourished in the Indus River basin and is characterized by the development of major cities, e.g. Harappa (Pakistan) and Mohenjo-daro (Pakistan) with 35,000–40,000 inhabitants. Natives were the first users of water in the valley, and their use dates back to around 10,000 years. Mohenjo-daro, built around 4450 BP in a semi-arid environment, was serviced by at least 700 wells both public and private, about 15 m deep (Viollet 2000; De Feo et al. 2011, 2013). India has been facing water scarcity since antiquity and groundwater was a major water supply source, as it could be easily abstracted from shallow aquifer systems (Dugger 2006). In the 1st century AD, the slippery shores of the major rivers were tamed by the construction of ghats, long, shallow sets of stairs and landings. The same approach was applied to the construction of a new type of well, named stepwells. The earliest stepwells most likely date to about 550 AD, but the most famous were built in medieval times.

Ancient China also developed water wells using groundwater from their early stages. For this purpose, a drilling tool for water wells was developed, similar to modern drilling machines. China has a long history in the construction and use of wells. The distribution of water to the households by the construction of water supply networks generated from the late 19th century in some major cities. Until this period, water was provided from wells and from rivers near wells. Water from wells was more popular for daily use, because it was more convenient since it provides a stable water supply and has better quality characteristics in comparison to river water. People believed that some wells produced good tasting water and the river water was used mainly for washing. Furthermore, in China, as it was an agricultural based country, the wells have been also been used to cover the irrigation needs in the rural areas. According to the discovery, the use of wells for irrigation purposes dated back to ca. 2nd century BC (Hu 2006). Based on the C-14 dating of the well wood, it was concluded that the oldest well in China was built in 5710 ± 125 BP (Zhou et al. 2011).

This review article deals with the development and use of groundwater by applying water wells technologies through the centuries. Emphasis is given on the history and evolution of wells as a water source. Furthermore, representative examples of water wells that chronologically extend from the prehistoric times to the modern times are presented. These examples may have some importance for hydrogeologists and water engineering even in modern times.

**BALKAN CIVILIZATIONS**

**Greek civilizations**

**Prehistoric times**

In the Minoan palaces (Crete Island, Greece) and other settlements, water supply was differentiated according to
local hydrogeological conditions (Mays et al. 2007). Thus, in eastern and southern areas with low water availability (e.g. Zakros, Palaikastro, Fourni, Komos), the water supply was dependent on groundwater and rainwater (harvesting). In these areas, water wells and cisterns were highly practiced. Even in Knossos, wells were mainly practiced in the early times (Angelakis & Spyridakis 2010). Six of them, which were used for drawing drinking water, have been reported (Evans 1964). Their depth was less than 20 m and their diameter did not exceed 5 m (Buffet & Evrard 1950). Also, in the Zakros palace, a well-spring is located near the southeast corner of the central court. Finally, the Palaikastro city was entirely dependent on groundwater. Several wells have been discovered so far with depths ranging from 10 to 15 m (Figure 1(a)).

Mycenae, located in the northeastern Peloponnese (90 km from Athens), is considered the center of Mycenaean civilization (ca. 3600–3100 BP). The Mycenaean civilization flourished in the late Bronze Age (ca. 3500–2200 BP) and at that time they extended their influence up to the Aegean Sea mainly in Crete and the Cycladic islands. Thus, Mycenaeans were probably influenced by the Minoans which had also spread to Aegean islands (Angelakis et al. 2012). At this time (ca. 3350 BP) the citadel in Mycenae was extended. The citadel-wall was moved to the northeast, with a secret passage through and under the wall, of special construction, leading downward by 99 stone-made steps to a water well carved in the rock (Figure 1(b)). The steps are interrupted by two landings at the point where they turn. At the far end of the passage, at a depth 18 m, is a quadrilateral roofed shaft receiving the water by a tunnel from a spring above the ground surface. The well was the basic reason for the extension of the northeast wall of the citadel.

The well is considered the most spectacular achievement of Mycenaean building art. Stepwells that are accessible by stair steps have been known since the prehistoric times. A small room under the surface was used as spring-basin or draw-basin. The water was collected in the middle of the basin and people transported the water into bowls or with pipes to the surface. These step-wells were 12 m deep, 2 m high and 4 m wide (Tuttahs 1998; Kramer 2002).

**Historical times**

According to myth, Goddess Demeter rested as she searched for her daughter Persephone. In Attica, there have been identified wells since ca. the 3rd millennium BC. There, digging of wells was a common practice all over the city, due to increased water demand, the local semi-arid climate, and the lack of springs and rivers.
This practice was more intense during the dry years, when numerous wells were constructed. In addition, early in the 6th century BC, Solon (638–558 BC), an Athenian statesman and lawmaker, was appointed as a lawgiver; he passed a law to regulate and encourage the use of wells (Angelakis & Voudouris 2014). A map showing the location of ancient wells around the Athens Agora is illustrated in Figure 2(a). It is pointed out that Agora means ‘a place of gathering’ and the Agora of Athens was the heart of Athenian life in ancient times (Lang 1968).

People in Greek cities, as in all the ancient world, used to obtain water directly from the earth, vertically below the spot where it was required, in parallel with the construction of complicated water transfer projects, aqueducts and urban water networks. They used to dig private and public wells of varying degrees of formality (size, cross-section, structural features and well-head configuration), reaching shallow sources or tapping deeper aquifers. A large number of wells has been reported throughout antiquity at strategic locations in every Greek city, usually equipped with cut toe holes for descending and cleaning. They have been found along main streets, in houses, or public buildings and complexes, such as Agoras, baths, palaces, sanctuaries, or cemeteries (Tölle-Kastenbein 2005; Kaiafa 2008). Many wells of Hellenistic and roman times have been found in the eastern and western cemeteries of Thessaloniki city, between the graves so as to facilitate the burial practices. The well known as Kallichoron well in Eleusis is of early classical times (Figure 2(b)). Its well mouth was constructed in ca. 6th century BC.

Regarding the cross-section of the wells of the Greek area, the vast majority were round; however, there are cases of badly made well shafts with an oval ground plan. The quadrilateral shape seems to be a random manufacturing option recorded both in northern and southern Greece (Kaiafa 2008, 2010; Kaiafa-Saropoulou 2014a, 2014b). A public well from Eretria, of the 6th century BC, confirms the presence of the quadrilateral contour in the Greek world since the Archaic period. Many rectangular wells in Rhodes and Kos evidence that this ground plan type had been preferred there since the classical era. In Macedonia, four-sided water pits seem to have been known since classical times, as it is confirmed by the existence of a rectangular, monumental, public, early 5th century BC well in the Agora of Thasos. This type of square well shafts was maintained in
the Greek world until after the end of the antiquity, in the Byzantine era (Kaiafa 2008, 2010).

In their simplest form, wells were left unlined, in some cases they were dug through soft rock or clay. A large number of unlined wells were found both in Olympia, around 150 and in Athens up until the 4th century BC (Lang 1968). Very rarely they were smeared with a thin layer of white clay just like uncoated wells in many locations of Roman Britain. Apart from this costless practice there are three more categories related to the well shafts’ formation that can be mentioned (Kaiafa 2008; Kaiafa-Saropoulou 2014a). The simplest lining for round wells were drums stacked on top of the other. Terracotta lining of water shafts has been quoted to two coexisting practices, rings of one piece each, lowered into the well hole, and drums made up of three or more sections. The second variation is identified both in Macedonia (Pella, Amphipoli), but especially in southern Hellas from Minoan times until the late Roman period in Crete, Eleusis, Argos, Delos or Naxos. In Athens, where digging of wells was a standard practice all over the city, due to increased water demand and the lack of springs and rivers (Camp 1977; Chiotis & Chioti 2012), nearly all the well shafts of the 4th century BC have been formed by multi-membered drums. However, the most common forms of wells were those lined with stone masonry in two basic variations, the rough stone masonry, dry joined or mixed with lime mortar, and the more elaborate with stone blocks in rows. The non curved-stone masonry during Roman period was usually combined with the widespread use of scattered parts of bricks and tiles or broken pottery, sometimes plastered with lime or hydraulic mortar.

Wells made of stone blocks in rows are represented by few examples, scattered in all over Greece, in Potidea and Arta, for example. Their entire shafts were lined with ashlars of varied heights carefully curved so as to accomplish the circular cross-section. Isodomic masonry of curved stones has been also revealed in many wells in Pella, where from their total depth only the upper part of the shaft was stone coated, while the lower has been left unlined, thus it was dug through exceptionally hard rock, until the aquifer was reached (Kaiafa 2008; Kaiafa-Saropoulou 2014a).

A notable example of a hewn stone built well, from the 2nd century AD, has been found in Plotinopoli of Thrace, (Hellenic Net 2009) unique in the whole region. Its shaft was lined to a depth of 7.50 m, and it continued on down, cut into the natural rock (Figure 2(c)). Water could be safely drawn not only from the well mouth but also from an arched opening with a protective vertical stone slab at the north side which led to a rectangular vaulted chamber (Koutsoumanis 2001, 2005). Finally, brick lining represents another technique, already known from Assyrobabylonian architectural types, since the 9th century BC. It was preferred in many wells of the 1st century BC in Olympia. Wells of this category were formed by special bricks with their long sides curved so as to cover the round shafts. Sometimes bricks of the special curved shape were placed in independent rows in sequence with lime mortar lined the hole shaft, while in other cases, bricks created a continuous spiral, without mortar, progressing from bottom to top of the round shaft, forming the well.

Although the majority of data related to the well mouth configuration are lost forever, there is no doubt that wells in antiquity were usually provided with a well-head of terracotta, wood, stone or marble, to stop objects and people from falling in. Moreover, they also had a movable cover or lid, in order to restrict the evaporation. Among the evidenced elements are both tall and projecting well heads, placed over the water mouth, and lower formations, almost unified to the shaft configuration. Stone rings around well mouths with or without a stone pedestal are worth mentioning, as well as stone bases, monolithic, two-sectioned or multi-membered, placed over the well openings or, finally, four-sided compact constructions build of mortared stones framing the well mouths (Kaiafa 2008; Kaiafa-Saropoulou 2014a, 2014b).

Drawing water from wells is directly related to the forms of well heads. People all over Hellas used to lift water from underground aquifers to ground level either manually or by using mechanical devices. Water was hoisted up using jugs or buckets of clay or copper, on a rope or a chain driven by human or even animal power. Traces of rope marks have been found on many wellheads in the form of worn deep grooves on the lips, due to the repeated friction. Apart from the simplest method of shaduf, the technical solution of hoisting water up from deep wells, known since the 8th century BC, was to run the bucket rope over a pulley, usually of wood, hanging centrally above the well. These lifting mechanisms were supported on two or four upright members which were relaying on carved holes, placed
around well mouths. Sometimes, in parallel with the function of the rotating wheel, water was also reached manually, by a rope (Kaiafa 2008; Kaiafa-Saropoulou 2014a).

**Byzantine to mid-modern times (ca. 400–1800 AD)**

In the ages after the fall of the Roman Empire, water supply remained a crucial issue in everyday life. The importance of wells in domestic and public supply has been evidenced during the Byzantine era all over Greek world, in spite of the fact that, in many cases, the water supply was mainly based on cisterns where rainwater was harvested and stored. Very often, wells were used in addition to underground cisterns. In Iraklion city in Crete, several well curbs of Byzantine times (Figure 3(a) and 3(b)) have been found in excavations; they were usually made of marble and decorated with sculpted figures (Strataridaki et al. 2012).

During Venetian rule (1205–1669), when the island was very much exposed to Renaissance culture, water supply depended both on water cisterns and wells. The mouthpieces of two wells of that period are shown in Figure 3(c) and 3(d) (Strataridaki et al. 2012). The main water technologies applied at that time were the wells for groundwater use and cisterns for harvesting and storing rainwater.

**Modern and present times**

As already mentioned, the wells mainly exploit the shallow aquifer systems (depth <20 m). The overexploitation which took place during the last decades of the 20th century provoked groundwater level decrease across the globe. Thus, many shallow wells have run dry and many deep boreholes were opened for water supply. The deterioration of water quality occurred as a result of human activities. All the rivers in India are polluted to some degree. The groundwater quality in wells violates the desired levels of dissolved oxygen and coliform. High concentrations of toxic metals, fluoride, and nitrates are locally recorded in many areas due to mining and agricultural activities. The polluted water then seeps into the groundwater and contaminates agricultural products when used for irrigation. Over 21% of transmissible diseases in India are related to polluted water (India 2002). Greece, China and Iran are also facing similar problems with both the quality and quantity of groundwater from shallow aquifers.

Borehole drilling has a long history. It is pointed out that a borehole may be constructed for other different purposes than water supply, e.g. extraction of petroleum or natural gas, mineral exploitation, geotechnical investigation, exploitation of geothermal energy, environmental assessment, etc. The first drilling rig was built in 1863 and a few years later in 1885, in combination with the development of technology, the first drilling rig was used by P.A. Craelius, a Swedish engineer, for geotechnical investigation.

The drilled wells are created using either top-head rotary style, table rotary, or cable tool drilling machines. Drilled wells can be excavated by simple hand drilling methods (augering, sludging, jetting, driving, hand percussion) or

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**Figure 3** | Well’s mouthpieces in Crete: (a) and (b) Byzantine monastery of Toplou in eastern Crete and the Historical Museum of Crete, Iraklion, Greece, respectively (photo by A.N. Angelakis); (c) and (d) marble curb of the 15th century excavated in the center of the city of Iraklion (Strataridaki et al. 2012).

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machine drilling (rotary, percussion, down the hole hammer). Deep rock rotary drilling method is the most common method. Rotary drilling technology became common in the early 20th century and can be used in 90% of geological formation types (alluvial, carbonate, fissured rocks, etc.).

Modern drilling rigs are high performance and require limited manual work. They have the ability to drill in depths greater than 2,000 m. The deepest borehole for water supply in Greece exceeds the depth of 600 m and was constructed in Crete. Typically, a borehole is completed by installing a vertical pipe (casing) and screen to stabilize the sides of the hole and prevent sand movement into the borehole, and to allow a maximum amount of water to enter (Todd 1986).

Other Balkan civilizations

A Neolithic water well with a diameter of 1.5 m and a depth of at least 4.9 m has been found in Croatia at Zadubravlje: the well is dug in the ground and has at one side thin posts lined up as a protective fence. Charcoal samples from the bottom of the well have been dated by C-14 analysis to ca. 6610–6340 BC (7620 ± 140 BP) (Minichreiter 2001).

Recently, a water well has been discovered in the chalcolithic settlement of Solnitsata in Bulgaria (Nikolov 2012). At the northwestern thresholds of the Balkans, an established tradition of well construction can be recognized also in present-day Slovenia, where several prehistoric water wells have been excavated in the Prekmurje area, with one specimen at Lipovci dating back to ca. 6000 BP and other examples from the Bronze and Iron Age, one showing wooden lining (Dular et al. 2002; Šavel & Sanković 2010; Kerman 2011; Šavel & Karo 2012).

Seven wells have been found in the settlement of Ormož dating between the 10th and the beginning of the 6th centuries BC: wells there are divided into two groups: the first is simply dug into the ground, the second group shows an almost quadrangular wooden construction fixed by timbers and clay (Dular & Tomanić Jevremov 2010).

Later on, Roman wells with wooden lining have been again excavated in Prekmurje in Slovenia (Šavel & Kerman 2008). Several Roman wells have been found especially within the Roman towns, so also in Ljubljana, the ancient Emona, where water supply was in the ca. 2nd and 3rd centuries assured also by at least two aqueducts: one of the best preserved Roman wells in the town was 6 m deep with a diameter of 1.7 m, with a wooden box at the bottom used as basement and stone mortar-bound facing (Gaspari 2010). Roman wells have been also found in several sites in Croatia (e.g. Brijuni: Vitasović 2008; Virovitica Kiškoriaj south: Jeličić Vučković 2015) and in Serbia (Stevanović 2013), Bosnia and Herzegovina (e.g. at Ljubuški), as well as in Bulgaria (e.g. Nicopolis ad Istrum near Veliko Tarnovo).

INDUS VALLEY CIVILIZATIONS

The Indus-Sarasvati civilization had developed many reservoirs to collect rainwater (ca. 5000–3500 BP). It is usual that each house has an individual well. Ancient Indian scriptures made references to the construction of wells, canals, tanks and dams and their efficient operation and maintenance. The practice of irrigation was used in producing food grains and has been known for over 5,000 years (Framji 1987; Krishnamurthy 1996).

The wells are called many names. During ca. 5000–3500 BP, Indus-Sarasvati civilization had several reservoirs to collect rainwater runoff. Each house had an individual well. In Hindu they are baori, baoli, baudi, bawdi, or bavadi. Ancient Indian scriptures made references to construction of wells, canals, tanks and dams and their efficient operation and maintenance. The practice of irrigation as a means of producing food grains is known to have been in vogue for over 5,000 years (Framji 1987).

The architecture of the wells depended on where and when they were built. Two common types are a step pond, with a large open top and graduated sides meeting at a relatively shallow depth. The stepwell type usually built a narrow shaft, protected from direct sunlight by a full or partial roof, ending in a deeper, rounded well-end. Temples and resting areas with beautiful carvings were built into many of the wells (India 2002). The use and conditions of stepwells began to decline in the years of the British Raj, who were horrified by the unsanitary conditions of these drinking water bathing spots. They began to install pumps and
pipes, and eventually outlawed the use of stepwells in some places. The remaining stepwells are in varying states of preservation, and some have gone dry. Local kids seem to find the ones with water to be terrific diving spots, which seems extremely hazardous (CWC 1987).

Stepwells were accessible by stair steps. A small room under the surface was used as spring-basin or draw-basin. The water was collected in the middle of the basin and people transported the water into bowls, jars or with pipes to the surface. These step-wells were 12 m deep, 2 m high and 4 m wide (Kramer 2002). With this system water could be grained even in very deep aquifers.

Chand Baori in Abhaneri, near Jaipur, Rajasthan, is among the largest, if not the largest, and perhaps the most visually spectacular stepwells. Chand Baori is a deep four-sided structure with an immense temple on one face. The construction dates to the 10th century, and is dedicated to Harshat Mata, goddess of joy and happiness. Rani Ki Ji Baori, Bundi, Rajasthan is sometimes called ‘The city of stepwells’ for the more than 50 wells in and around the city. The Rani Ki Ji, or ‘Queen’s Stepwell’ is the most famous. It was built in 1699 by the spurned second wife of the king, who was cast aside after she bore him an heir. She turned her energies to public projects, building nearly 20 wells, including the 46 m Rani Ki Ji, 1 m wide at the top, with 200 steps that descend to the water. The stepwell at the lost city of Vijayanagara, Karnataka in the lost city of Vijayanagara there is a large pond-style step well near the ruins of Hampi, similar to Chand Boari, but with four symmetrical sides.

At Agrasen Ki Baoli, more than two months of digging removed centuries of silt and trash from the Agrasen well in Delhi (Kochar 2017). Located close to the famous Jantar Mantar observatory, the well is deep and rectangular in shape, 60 m long by 15 m wide, with 103 steps, some of which are submerged. The construction dates are unknown, but it most likely dates to the mid 1300s. A new appreciation for these wells comes both from renewed cultural and architectural pride, but also in realizing that the ancient system of holding water still makes a lot of sense. The multistory step well constructed in Rajasthan is shown in Figure 4(a). The hand-dug well cased with concrete rings is shown in Figure 4(b). Chand Baori stepwell is one of the most overlooked landmarks in the country, consists of 3,500 narrow steps over 13 stories, making it one of the deepest and largest stepwells in India which is shown in Figure 4(c). It is one of the oldest and most attractive landmarks in Rajasthan and also the most visually spectacular stepwell in India.

Construction of stepwells involved the sinking of a typical deep cylinder from which water could be hauled. The careful placement of an adjacent, stone-lined ‘trench’ was made with a long staircase and embedded side ledges, and allowed access to the ever-fluctuating water level which flowed through an opening in the well cylinder. In dry seasons, every step had to be negotiated to reach the bottom storey. But in rainy seasons, a parallel function kicked in and the trench transformed into a large cistern, filling to capacity and submerging the steps sometimes to the surface.

Figure 4 | View into a hand-dug well cased with concrete rings: (a) multistory stepwell, (b) dug well, and (c) Chand Baori stepwell.
This ingenious system for water preservation continued for a millennium (India 2002). The earliest stepwells most likely date to about 550 AD, but the most famous were built in medieval times. It is estimated that over 3,000 stepwells were built in the two northern states. Although many have fallen into disrepair, were silted in at some point in antiquity, or were filled in with trash in the modern era, hundreds of wells still exist.

CHINESE CIVILIZATIONS

Chinese early history

The history of wells in China dates back to ca. 6174–5921 BP that, according to the earliest well ruins, were discovered in He Mu Du of Zhijaing province in 1974. In these ruins, a wooden well was discovered, which was the earliest in China (Zhijaing Provincial Museum 1978). Later, many sites of wells were discovered that show that the well was popularly used in ca. 5000–3000 BP. For example, wells discovered at the Jingsha Ruins in Chengdu City dated back to around 4,000 years, proving an advanced well making technology since then. In 2008, a well of the Qin Dynasty (221–207 BC, the first united dynasty of China), was discovered in Xi’an City, which was the earliest discovered with many Qin remains at the Yellow River basin.

In general, the early civilization of China emerged in the mid basins of the Yellow River and the Yangtze River. Wells’ use in the Yangtze River basin was earlier than in the Yellow River basin, around 1,000 years, due to the aquifer in Yangtze River basin being higher than the Yellow River basin; the above mentioned He Mu Du well ruins are located at the Yangtze River basin. Accordingly, the well in the Yangtze River basin usually had a depth of 2 m. The walls of the well were made of the wood, but the well in the Yellow River basin was made deeper and more difficult due to the lower aquifer and hard soil (Hu 2006).

After the wells’ use, the residing areas were able to spread from the riversides. People could settle anywhere they could construct wells for water supply. The structural feature of the well was developed in different ages. According to the archaeological discovery, the early well (around 5000 BP) was built with wood, the form was square usually. In the Fighting-States period (475–221 BC), the well walls were built with earthenware since it was a very popular structural material in that age.

Later Chinese dynasties or the Han, Song and Yuan dynasties

In the Han Dynasty (ca. 202 BC–220 AD) and subsequent dynasties, before the Song Dynasty (960–1279 AD), wells that were built with brick became more popular. They were more firm and diversiform (Liu 1991). But it is the fact that in the Han Dynasty, the wells were still built with wood, earthenware and brick depending on the local conditions. Sometimes the wells were a mixed construction built with wood and earthenware. An earthenware well of the early Han Dynasty, that was discovered in Yeng county, Hebai province, is an evidence of earthenware use for building of well in that age is shown in Figure 5(a) (Zheng & Angelakis 2018). According to the report, about 40 wells were discovered in the same ruins. The depth of each well is from 5 to 7 m and its diameter is 1.3 m (Zhao 2010), located at the Yellow River basin.

In this period or even earlier, the wells were used for residence as well as for irrigation of the farmland in the Yellow River basin; this situation was an important progress for the irrigation to spread to agricultural activities in large areas. They also developed the techniques for well water use, e.g., put the well water in an open place to warm it before use due to the temperature of the well water being too cool for the crops. A pumping facility was also popularly used above the well walls for convenient water use according to many Han earthenware models of wells that were discovered (Figure 5(b)). Anyway, the Han well ruins were discovered popularly in China from north to south that evidenced that wells were widely used in China in the Han Dynasty.

After the Han Dynasty, wood and earthenware were disappearing, especially in major cities. Since the Tang Dynasty (618–907 AD), the brick well-structure became popular in the residential areas (compared to the irrigation well in the farming areas); at same time, people liked to build a stone structure above the well, and made it more firmly, beautifully and with complex social and even holy meanings. After the Song Dynasty, a stone structure above a well became popular and was more focused on its artistic modeling. Since then, the stone structure of the well became the main stream of the
well construction. People did not just build the well in beautiful designs but also in different models, for example, there were two or more water hole above one well (Figure 5(c) and 5(d)).

During the Yuan Dynasty (1271–1368 AD), wells were more popularly used for irrigation. That means that wells were not just for domestic use but also functioned as the irrigation in the semiarid areas. Well dependent irrigation was developed on a large scale in Fujian Province and Shanxi province, almost every piece of farmland with a well (Wu 2002).

Anyway, after the Yuan Dynasty, wells’ use was popular for irrigation and manufacture, as well as for daily water from rural areas to urban areas. In the urban areas, wells were the main water resource for daily life, especially for drinking. Usually, there was a public well for a community, but a family with a private well inside the house was common, especially for some rich families. At the same time, wells were also the main water resource of urban manufacture in many cities. It was popular that much traditional food was strongly dependent on the quality of the water supplied by wells. A paradigm is the bean curd manufacture in Jinshui City of Yunnan province which has been dependent on a special well.
to keep the taste and quality for hundreds years until
today.

In the rural areas, wells were used for daily life as well as for irrigation; usually every village had one or two wells but, at the same time, a family would also have a private well. According to the statistics in 1949, about 1,500,000 ha farm-lands were irrigated by wells and the productivity of wells for half a ha averagely (China Academy of Agriculture Sciences 1973). The wells withered away from the 1980s in major cities due to the groundwater control, urbanization and tap water convenience. Today just some small or remote cities still keep wells in use. In many rural areas, the well-based irrigation has collapsed due to the development of pumping facilities and declining groundwater, but the well for daily water in the village, especially in the remote areas, still exist, but it is also challenged by current rapid urbanization and groundwater declination, water pollution, etc.

Well is the end structure of water use, but consider its importance with the daily life and production. People are not just considering it as a water facility but also a special place where there are embedded rich meanings, popularly it is the holy place where the dragon, the God of water’s place, or the place of the God of the community or village. Accordingly, people usually built it as artistically as possible in different ways, including beautiful structures above and other decorations. For example, the Shang eight-hole well in Hangzhou City which was constructed in the Song Dynasty is one of the famous scenic spots of the city. Local people built eight water hole structures above the well, but it is only one well under the structures. The purpose of the design not just made it so that more people can use water in same time but also specially. A broadly social relationship was structured based on the well, due to the well being the place people have to meet every day in a residential place. People have to manage and balance the economic benefits of the well water resource in a community and take festival or worshiping activities that related to the well.

Anyway, the well usually becomes an important cultural center with religious, social, and artistic meaning; the well related culture also became a kind of water culture, simultaneously, it was also validated that the well-related water culture functioned the role of well protection. Usually, every village has one or two public wells for water use; it is an important spiritual center of the village because when a place was considered to build the village, the villager has to find a place to build a well, and it means that building a well is the first thing to be done before a village was built (Zheng 2003, 2014). Even today, tap water has popular use but more villages still follow their tradition to use well water for drinking and cooking. One paradigm is the well in the Dai area of Yunnan province. Two different types of Dai wells are shown in Figure 6.

**PERSIAN EMPIRE**

The first effort to extract groundwater in western Persia and northern Mesopotamia by using a series of water wells,
20–30 m apart, belongs to the Persian Empire (2,500 years ago). Considering slope instead of lifting devices was the advantage of that system. These wells were replaced by other engineering systems such as great dams and deep water wells (English 1968, 1998; Afshar 1981; Bazza 2007; Harandi & de Vries 2014). According to Molle et al. (2004), in villages, the development of wells has impacted on qanats and the water table of groundwater.

In the Persian Empire, water harnessing projects, such as digging water wells and building of dams and reservoirs to irrigate agricultural lands and to harvest rainwater, respectively, have been considered (Afshar 1981; Ettehad 2010; Harandi & de Vries 2014). In 546 to 331 BC, there is evidence at the Persepolis complex (Mays 2010; Hejazi et al. 2015; Yannopoulous et al. 2015). In Rahmat Mountain, there is a stone water well that exhibits a furnished portable water system at the Persepolis complex. There is no historical study on water systems of the complex. However, there are two different types of water engineering in the complex. First, there is a deep well (about 60 m) in the south of the complex and a long conduit (about 180 m). These two hydraulic structures controlled runoff to reduce the risk of floods in the Persepolis complex. Furthermore, there is some evidence of the conservation of urban runoff from sources of pollution in the Persian Empire (Niemczynowicz 1997). In the Empire, polluting water resources or drinking water was considered a great sin. Deep water wells were used to inject runoff into the aquifer zones. However, this attitude was changed during this time (Burian & Edwards 2002). Another example of Achaemenids’ water wells are Laft water wells in Qeshm (Figure 7).

Figure 7 | Laft water wells belong to the Achaemenids (546–331 BC). Residents of Laft obtained their fresh water from a series of circular wells; local legends say that there were 365 different wells – one for each day of the year. (a) The presence of the trees suggests that most of them have water; (b) some of the wells are still in use for local residents; (c) Laft wells after a storm rainfall event; and (d) situation of the wells under water.
On the landward edge of Laft, the ruling sheikh’s fort still stands, albeit crumbling. Behind the fort, in a series of limestone basins, lies the Laft’s water supply: a series of bored fresh water wells. Local traditional says there are 365 of these, a different one to be used for each day of the year. However, nowadays there are only 100–150 of the wells which have been dug in schist. The gypsum layer, at the end of the wells, leads to fresh and cold drinking water for a long time. Each well has been named on the basis of shape, type of its water, and other attributes. For instance, some of names are Sardu, Lubni, Darjai, Domaron, Satbi (Sagi), Rigi, Talkhu, Ashuri, Kenti, Kenari, Mion Talaei, Pa Saghfi (Pa Sagi), Lufarauni, Kami Ziarati, Goravi (Gorbeh), Lufarani, Luhegami, Karbi, Lurikanizun, Burki, Gharabu, Zidel Gharabu, and Dariguzi. The layout of the wells leads to collecting runoff of storm rainfalls, which are the only source of fresh water in Laft, across the mountains. The depth of the wells ranges from 3 to 6 m. Due to the high value of water in Laft, these wells are also called Tala (gold) wells. However, the correct name is Tal Eau (eau refer to water in ancient Persia and in today’s French). The traditional beliefs say that the trees protect the wells. Local people considered sacred the wells and trees of the region as well as they sacrifice some of their animals close to the wells and under the trees’ shade.

Another instance of ancient water wells of the Persian Empire belongs to the Sasanian Dynasty (224–651 AD) called Siraf stone water wells in Bushehr. Siraf is the greatest historical port in Iran. It was the center of trade exchanges between the Persian Empire, Egypt, India, China, and Africa. Two terrible earthquakes led to the ruin of a part of the port which went under water in 947 AD and 1116 AD. Similar to the Laft water wells, the layout of Siraf stone wells leads to collecting runoff of storm rainfalls, which are the only source of fresh water in this port, across the mountains of Siraf. There are 100 stone wells in this region. The depth of some of them is more than 130 m which have water in some of the seasons. If you drop a stone into the well, you will hear its sound after a few seconds. The type of digging wellhead and smooth and accurate cutting inside them are wonders of this area.

Some researchers reported that the first water well of Iran was dug simultaneously with the first Qanat. However, discovered water well (ca. 2,000 years ago) in Kalek-e Züräntel (a populated place) located with a 17 ha area in Pol-e Dokhtar in the south of Lorestan province may be evidence of the first water well with a riprap wall in Iran. In the current status, this well has a diameter equal to 1 m and a depth of 12 m and the riprap wall continued to the end of the well by using marl (Figure 8). The well was dug on the slope of the hill (towards the erosive valley) in silty-clay soil with low permeability. Approximately 5 m of the wall has fallen due to the erosion of the natural environment and 7 m remains in safety (Figure 8 top).
During archeological excavation, 3 m extra were also dug to characterize the depth of the well. In this depth (15 m), the well was still vertical and with riprap wall. However, more drilling to discover the side gallery was not possible owing to the risk of the wall falling. In order to justify hydrogeological use of the well in the study area where there are a lot of surface water resources such as springs and rivers, Figure 8 (bottom) was plotted (e.g. Kashkan, Saymareh, etc.). Since there is no water limitation in this region, drilling the well, in ca. 234 BC–1310 AD, refer to social aspects of water wells. It may be considered easier to access the water resources of the erosive valley for settled peoples or a sense of security within the territory as the reason(s) for digging the well. The structure of dry stone employed for this well reveals the skill of pitman.

In addition, the materials have been available for dry-stack method using marl. Anyway, this is a vertical well that it has been designed and dug for extraction of surface and ground waters (drainage) of clay layers in which there is gully erosion. If there is a radial gallery (Figure 8 bottom), it may be accounted by the oldest discovered well close to river-like river backfiltration (RBF) in Iran (Falcon & Harrison 1937; Ray et al. 2003; Clapham 2004; Saghafian 2005; Taheri & Garavand 2012).

DISCUSSION AND CONCLUSIONS

Groundwater, together with surface and springwater, have been sources of water supply since the dawn of human history. The technology of wells was an important activity for the water supply of urban areas in regions under low water availability or during wars and other conflicts since prehistoric times. One of the most prominent features of prehistoric civilizations (e.g. Minoan, Indus Valley and Mycenaean) was the hydraulic construction and operation of water supply systems in urban areas such as construction of wells in the areas with limited water sources (e.g. Palaiokastro town in the eastern Crete, Mohenjo-daro, and Mycenae).

This review provided valuable insights into the art of wells construction, developed in several regions of the world (e.g. Balkan Peninsula, Iran, India, and China). The examples that are briefly described above prove that wells, private or public, remained an important source of water supply since antiquity. It is also pointed out that the history of water wells is marked by developments in different fields such as hydrogeology, soil mechanics, geophysics, and marine geology. The construction of wells varied according to local conditions, determined by geology, hydrogeology, and geomorphology, as well as to the local tradition.

Regarding the Balkan Peninsula, archaeological data witnessed that people in the region of Greece used to reach shallow sources or tap deeper aquifers by digging wells, which were usually coexisting, supplementary, with large scale water transfer projects (aqueducts). The wells in ancient Greece were always easily reachable, usually round, their depths depended entirely on the water table and local geological conditions, and the shafts’ coating presents no major changes over time. Other areas of the Balkans (Slovenia, Croatia, Serbia, and Bosnia) show an evolution of wells developing from local prehistoric traditions. Several Roman wells have been found, especially within the Roman towns in the North Balkan Peninsula.

In many sites of China, wells were popular during the period ca. 5000–3000 BC. Furthermore, a well was not just a water source but also became a cultural symbol in the history, related to local religion and custom. The study of ancient wells can give important information of the experience and knowledge of ancient civilizations.

A stepwell is a characteristic type of well developed in India and were used as tanks for water storage during the dry period in order to cover the irrigation needs. However, this type of well was known in Hellenic civilizations since prehistoric times (e.g. in Minoan and Mycenaean civilizations). The stepwells in India became not only sources of drinking water, but cool sanctuaries for bathing, prayer, and meditation. Water has played an important role in the architectural heritage of western India from the earliest times. One of the most characteristic features of the early Harappan towns (ca. 5000 BP) was the presence of a sophisticated system of tanks (water storage structures) and wells. The practice of making wells into an art form was begun by the Hindus but it developed under Muslim rule.

In the Persian Empire (in Iran), due to frequent drought, thoughtful attention was paid to the reliable design of water
wells. Some researchers reported that the first water well of Iran was dug simultaneously with the first Qanat. There are hand dug water wells still in use today in parts of the Persian Empire which were constructed more than 3,000 years ago. Persepolis well, Laft water wells, Siraf stone wells, and Kalek riprap well are only some of the historical water wells in ancient Persia. Hand digging of water wells was the principal technique of water well construction worldwide until the 19th century, when different types of drilling rig finally came into widespread use.

Finally, the aforementioned examples demonstrate that the Mediterranean and Asian peoples developed a sophisticated technique of well construction. These ancient hydro-technologies and practices applied from the past civilizations are important technological knowledge for new scientists dealing with groundwater exploitation.

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