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Review

Evolution of Water Lifting Devices (Pumps) over the Centuries Worldwide

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Abstract: The evolution of the major achievements in water lifting devices with emphasis on the major technologies over the centuries is presented and discussed. Valuable insights into ancient water lifting technologies with their apparent characteristics of durability, adaptability, and sustainability are provided. A comparison of the relevant technological developments in several early civilizations is carried out. These technologies are the underpinning of modern achievements in water engineering. They represent the best paradigm of probing the past and facing the future. A timeline of the historical development of water pumps worldwide through the last 5500 years of the history of mankind is presented. A chronological order is followed with emphasis on the major civilizations.

Keywords: Hellenistic Alexandria; Ancient Egyptians; Archimedes screw; Chinese Dynasties; Classical and Hellenistic periods; Indians; Bronze Age; Roman times; Persian Empire; piston-type pump; pre-Columbian America; shaduf

1. Prolegomena

Water is the driving force of all nature.

—Leonardo da Vinci

Water is an absolutely necessary element for life. The availability of water has played a key role in the development of all civilizations. Indeed, especially in the ancient times, water scarcity prevented the development of settlements.

In contrast to most ancient civilizations (Egyptians, Mesopotamians, Chinese, and Indians), which were developed where the necessary water for agricultural development was readily available, *i.e.*, close to springs, lakes, rivers and at low sea levels., all major Hellenic cities during the several phases of the Hellenic civilizations, which lasted for millennia, were established in areas that had low water availability. This was the case for both the continental and the insular country, since the Bronze Age [1]. This is in part attributed to the mountainous nature of the Hellenic landscape. Moreover, safety reasons and the efforts to avoid the vulnerability associated with the occupation of low sea level fertile lands, resulted in the construction of settlements on the top of hills or on rocky areas. It is probable that these factors limited the availability of water and contributed to the search for water, conveying over long distances, water saving and water lifting solutions [2].

Scarborough [3] and Ortloff [4] show how water management affected ancient social structures and organization through typical examples in the Eastern and Western hemispheres, covering the whole ancient world. Water transport over long distances was based on gravity. Thus, long aqueduct systems (indeed, sometimes exceeding 100 km) were used to convey water over large distances, using gravity. Also, water cisterns for harvesting rainwater, canals, and ground water wells were practiced since the Bronze Age (*ca*. 3200–1100 BC).

Securing water availability in regions of high altitude required the expenditure of energy. As electrical energy and energy from fossil fuels were unknown, manually operated mechanical devices, or devices driven by natural forces, such as wind, had to be invented. Such water lifting devices originate in the prehistoric times [5].

Water lifting devices have existed since *ca.* 3000 BC in various parts of the world [6]. Early devices, such as water wheels and chutes were constructed and used animals (muscle energy) to provide the energy required to move the wheels [7]. Later on, pumps, such as helicoid pumps known as “Archimedean” were invented and are still in use today. Also several types of water lifting devices known as “tympana” (drums) were widely used for irrigation and mining, until the past century [8].

In ancient Hellas, water lifting devices enabled the development of settlements in locations with low water availability and ensured not only the survival of the ancient Hellenes, but also improved the quality of their life. Ancient Hellenes not only devised several new hydraulic technologies, but also adopted and developed further the water lifting techniques of other civilizations [2,9]. According to Eubanks [10], Danus of Alexandria in 1485 BC dug the wells of Argus on the coast of Peloponessus and installed the Egyptian chain-o-pots as pumps, in place of the "atmospheric" or "force" pump. Meanwhile, other early civilizations (e.g., Egyptians, Chinese, Indians, and Persians) developed similar water lifting devices.

The scope of this paper is not an exhaustive presentation of what is known today about water lifting devices, related technologies and their uses. Rather, some characteristic examples in selected fields that chronologically extend from the prehistoric times to the modern times worldwide are presented. The evolution of water lifting devices through the centuries with emphasis on the major achievements is examined. The examples of water lifting technologies and management practices (not widely known among engineers), given in this paper, provide an understanding of the historical evolution to the current state of the art in water engineering, as discussed in a later section.

2. Very Early (Prehistoric) Times

2.1. Eshnunna/Babylonia and Mesopotamian Empire in Modern Day Iraq (ca. 4000–2000 BC)

The shaduf is known as the first device used for lifting water in several ancient civilizations. It has been referred to with different names, such as shaduf (*shadoof*) in Egypt, *zirigum* in Sumer, *denkli* (or *paecottah*) in India, *kilonion* or *kelonion* in Hellas, *daliya* in Irak, *picottah* in Malabar, *lat* in India, *gerani* or *geranos* in Hellenistic Egypt, *kilan* (from Hellenic word *kilonion*) in Israel, and *tolleno* in Latin regions [11].

It is a wooden hand-operated device used for lifting water from a well, a river, a cistern or a canal. In its most common form, it consists of a long, tapering, nearly horizontal wooden pole, which is mounted like a seesaw (Figure 1). It has a bag and a rope attached on one end of the pole, with a counter balance on the other [5]. The operator pulls down a rope, attached to the long end, fills the container and allows the counterweight to raise the filled container [12]. A series of shadufs were sometimes mounted one above the other. A typical water lifting rate was 2.5 m^3/d. A single shaduf could thus irrigate 0.1 ha of land in 12 h [13]. The Mesopotamians were known to lift water using the shaduf at around 3000 BC [6].

The shaduf was widely spread in the ancient world, and several ancient civilizations dispute its origin. It was invented in the prehistoric times probably in Mesopotamia as early as the time of Sargon of Akkad (Emperor of the Sumerian city-states in the *ca*. 23rd and 22nd centuries BC). According to [14], a shaduf is depicted on a cylindrical seal from Mesopotamia dated *ca*. 2200 BC. It is also still in use in Egypt and other countries [5]. In North Africa, a similar technique (called locally Diou or Dlou) was developed in the beginning of the *ca.* 12th century [15]. It was used to raise water to higher levels. Owing to the fact that it was well spread in India, Laessoe [16] has reported that the shaduf was invented in India.

2.2. Bronze Age (ca. 3200–1100 BC)

In the Minoan palaces and settlements, water supply varied according to the local conditions of climate (mainly rainfall), aquifer and terrain [17,18]. Thus, in settlements in South Eastern Crete (e.g., *Zakros*, *Palaikastro*, and *Komos*), the water supply depended heavily on groundwater. In Palaikastro, several wells have been discovered to date with depths ranging from 10–15 m [17]. There are indications that the Minoans were using the shaduf in the Meso-Minoan period (*ca*. 2100–1600 BC) in *Zakros* and *Palaikastro* wells [19]. It was widely used in Hellas during the Classical and Hellenistic periods [11].

2.3. Ancient Egyptians (ca. 3000–67 BC)

The shaduf, already in use in Mesopotamia, appeared in Upper Egypt sometime after 2000 BC, during the 18th Dynasty (*ca.* 1570 BC). This device allowed the irrigation of crops near river banks and canals during the dry periods of the year ([20] p.58). The system was refined later on, with the introduction of a pulley and animal traction for lifting water from deep wells. It is still used widely today for providing drinking water and for irrigating small land plots close to wells. The device was also adapted in the Arabian peninsula [21]. The shaduf led to an increase of the area under cultivation in Egypt by 10%–15% [22].

Other water lifting devices invented by the Egyptians are the waterwheel with attached pots, a waterwheel with water compartments and a bucket chain, which ran over a pulley with buckets attached to it. The Egyptian *shaduf* and the water wheel (or *noria* or *sania*) are probably among the earliest devices for lifting water to be used for irrigation and domestic water supply.

Figure 1. Shaduf used to raise water above the level of Nile for irrigation purposes in Egypt [21].

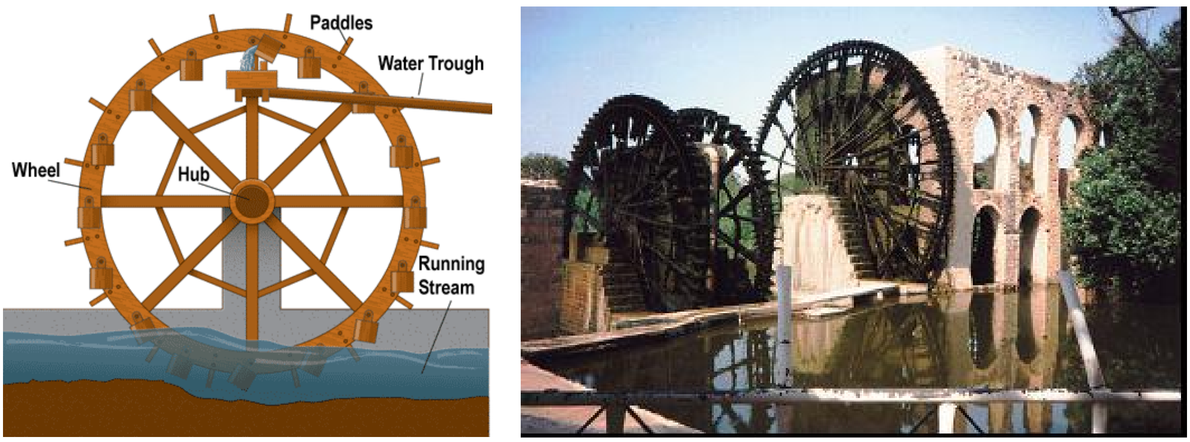
The Egyptian waterwheel (*noria*) is thought to be the first vertical (horizontal axis) waterwheel and was invented by the Romans *ca*. 600–700 BC. It consists of a wooden wheel, powered by water flow and fitted with buckets that lifted water for irrigating nearby lands. The diffusion of the Egyptian waterwheel is typically associated with the (later) Arab civilization and the animal-powered waterwheel is considered as the high symbol of the Islamic imprint upon irrigation technology. Also, the invention of the compartmentalized waterwheel in Egypt may have been made *ca*. in the late 4th century BC, in a rural context, away from the metropolis of Hellenistic Alexandria and was then spread to other parts of North Africa [23]. The hydraulic wheel was later built in Fez, Morocco, in the 13th century [24] and was then spread to other parts of North Africa.

Waterwheels driven by camels were used to lift water for irrigation and domestic use in Afghanistan and other Asian countries. A limited number of these units are still in use today. In Sudan, an ox-driven system has been used as a simple irrigation device for centuries and continues to be used even nowadays [21].

A variation of the Egyptian waterwheel is the Persian waterwheel. The date of its invention is not well known. It consists of an endless series of pots of unequal weight turned over two pulleys [10,25] and is therefore classified as a pump rather than a waterwheel. The delivery rate of early animal powered Persian waterwheels ranged between 20 m^3/h (for 1.5 m height lifting) and 10 m^3/h (for 9 m height lifting) [26]. Of course, the higher the waterwheel and the more advanced the technology used for its function, the more the quantity of water lifted. The waterwheel, in its different versions, constitutes the ancestor of dynamic water lifting devices and modern hydropower systems, the principle of which is to extract power from the flow (kinetic energy) of water.

The shortage of labour in the Middle Ages rendered machines, such as the waterwheel, cost-effective. The waterwheel remained competitive with the steam engine well into the Industrial Revolution [21]. The system used for lifting water to irrigate the Hanging Gardens of Babylon still remains a mystery. It is worth noting that the word *noria* is a Spanish word and its origin is coming from in the Arabic term, *Na-urah*, meaning *the first water machine*. In the related bibliography this word is found and as *Na'ura,* as well as *Naurah*.

The large-scale use of norias was introduced in Spain by Syrian engineers. An installation similar to that at Hama (Figure 2) was still in operation in Toledo in the 12th century. The *Na'ura* (*Noria*) of Albolafia in Cordoba also known as Kulaib, which stands until now, served to elevate the water of the river until the Palace of the Caliphs. Its construction was commissioned by Abd al-Rahman I, and was reconstructed several times.



(**a**) (**b**)

Figure 2. Waterwheel (Noria): (**a**) parts; and (**b**) in Hama on Orontes River in Syria (adapted from [27]).

Several civilizations claim the invention of Noria. There are Indian texts dating from *ca*. 350 BC; Joseph Needham believed that the noria was developed in India *ca.* the fifth or fourth century BC [27]. He assumed that it had then spread to the west by the first century BC and then diffused to China by the second century AD. This was followed by widespread use of the noria in the Eastern Mediterranean in the 5th century AD, before reaching North Africa and the Iberian Peninsula in the 11th century [27]. Other possibilities of its origin include the Near East *ca.* 200 BC. Philo of Byzantium in *Pneumatica* (*ca.* 230 BC), a Hellenic engineer of the late third or early second century BC, showed sketches of several distinct types of waterwheels [27].

The Tympanon was a structure, similar in use to the waterwheel (Figure 3). It was a wheel with a compartmentalized body. It took its name from the Hellenic word *τύμπανον* (*tympanon*) due to its resemblance to the drum or the tambourine. This device discharged a large water quantity quickly and it did not lift water to a great height.

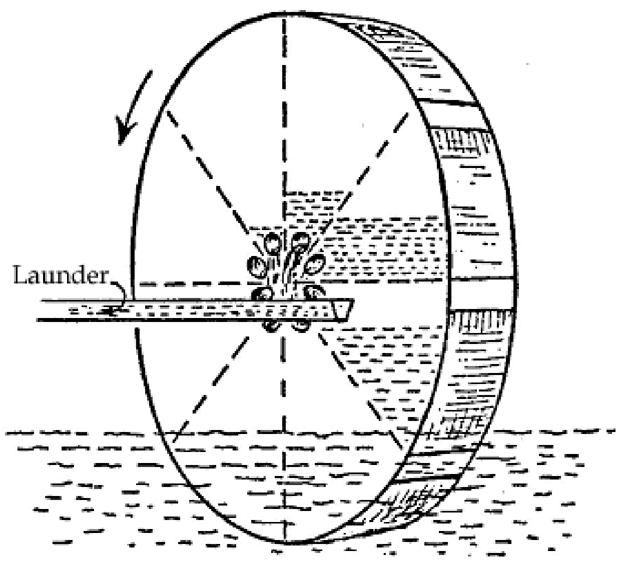


Figure 3. The *Tympanon* (adapted from [28]).

In case the water had to be raised higher, a wheel of a large enough diameter was mounted on the axle, so that it could reach the required height. Rectangular compartments were fixed around the circumference of the wheel and were made water-tight using pitch and wax.

Many waterwheels were rotated by men (Figure 4). Such a specific waterwheel was equipped with compartment rims that aided its operation. When the waterwheel was turned, the filled containers would be carried to the top of the waterwheel and on their downward turn would discharge the water they contained into a reservoir.

Similar to the waterwheel and the *tympanon* was the waterwheel-driven bucket chain. Due to its vertical movement it was used to raise water from deeper locations such as wells or rivers.

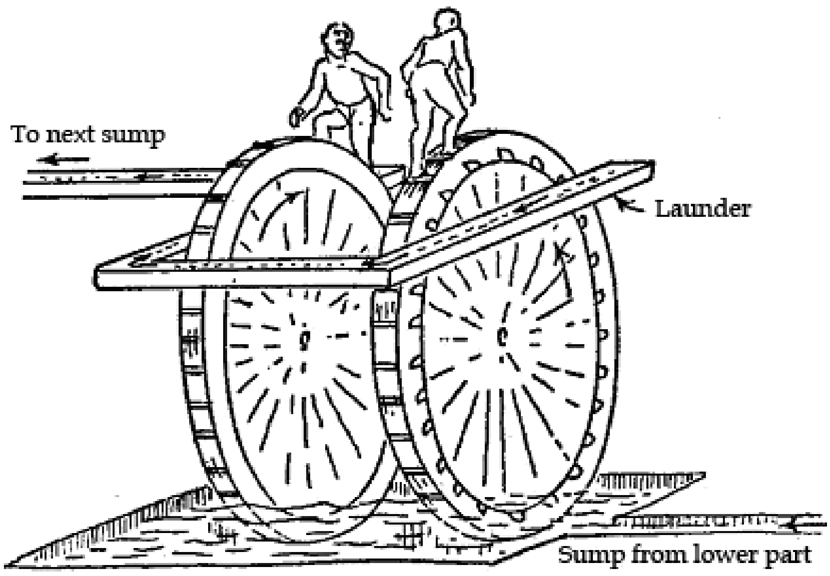


Figure 4. Waterwheels with *compartments rim*; representation based on archeological findings in Spain (adapted from [28]).

2.4. Ancient Persia (ca. 1200–200 BC)

The first traditional pumping method applied in ancient Persia was gravity based. If a water source was available at a higher elevation than its point of use, gravity can supply water via pipes or aqueducts. The Qanat is an example of this method and it was applied for the first time in Iran *ca.* 1200 BC [29,30]. The collection of rainwater from roofs or catchment areas and its storage in cisterns or as ground water was another possibility. Horizontal drilling was another reasonably easy and low cost method for tapping water resources in a way that would provide water without pumping, just by gravity flow. This is also an old method dating back to *ca*. 800 BC when the Persians began to dig the famous Qanats [30].

Like the Egyptians, the ancient Persians also used the shaduf, an old and simple device that evolved from the hand-carried bucket (see Figure 5a and [31]).

The original method of using animals to lift water was a device called mohte (Figure 5b,c). Here, animals walk in a straight line, down a slope, away from the well or water source, while hauling water up in a bag or container. Traditional mohtes used a leather bag to collect the water, but in recent years more durable materials such as rubber truck inner-tubes (or more rarely steel oil barrels) have been used. The Persian waterwheel (Raha) is a great improvement over the mohte, as its chain of buckets imposes an almost constant load on the drive shaft to the waterwheel (Figure 5d–f). Persian waterwheels are usually driven by some form of right angle drive. The first is the most common; the drive shaft from the secondary gear is buried and the animals walk over it; this has the advantage of keeping the Persian waterwheel as low as possible, in order to minimize the head through which water is lifted. The second example is a traditional wooden Persian waterwheel mechanism, which is based on the animal passing under the horizontal shaft. The sweep of a Persian wheel carries an almost constant load and therefore the animal can establish a steady comfortable pace and needs little supervision. The advantages of the Raha were: It was based on a relatively inexpensive traditional technology. It could be locally constructed and maintained, and lifted water up to 20 m (although it was most efficient at depths under 7.5 m and yielded of approximately 160–170 L/min of water for lifts of 9 m), it was easy to operate and it had medium efficiency (40%–70%). Hows [32] indicated the advantages of the Raha when compared to solar-powered pumps. The disadvantages of these devices were that water had to be raised above the point of discharge before falling into the collection channel, and that animals had to be maintained year round, even when irrigation was not necessary (rainy season) [33,34].

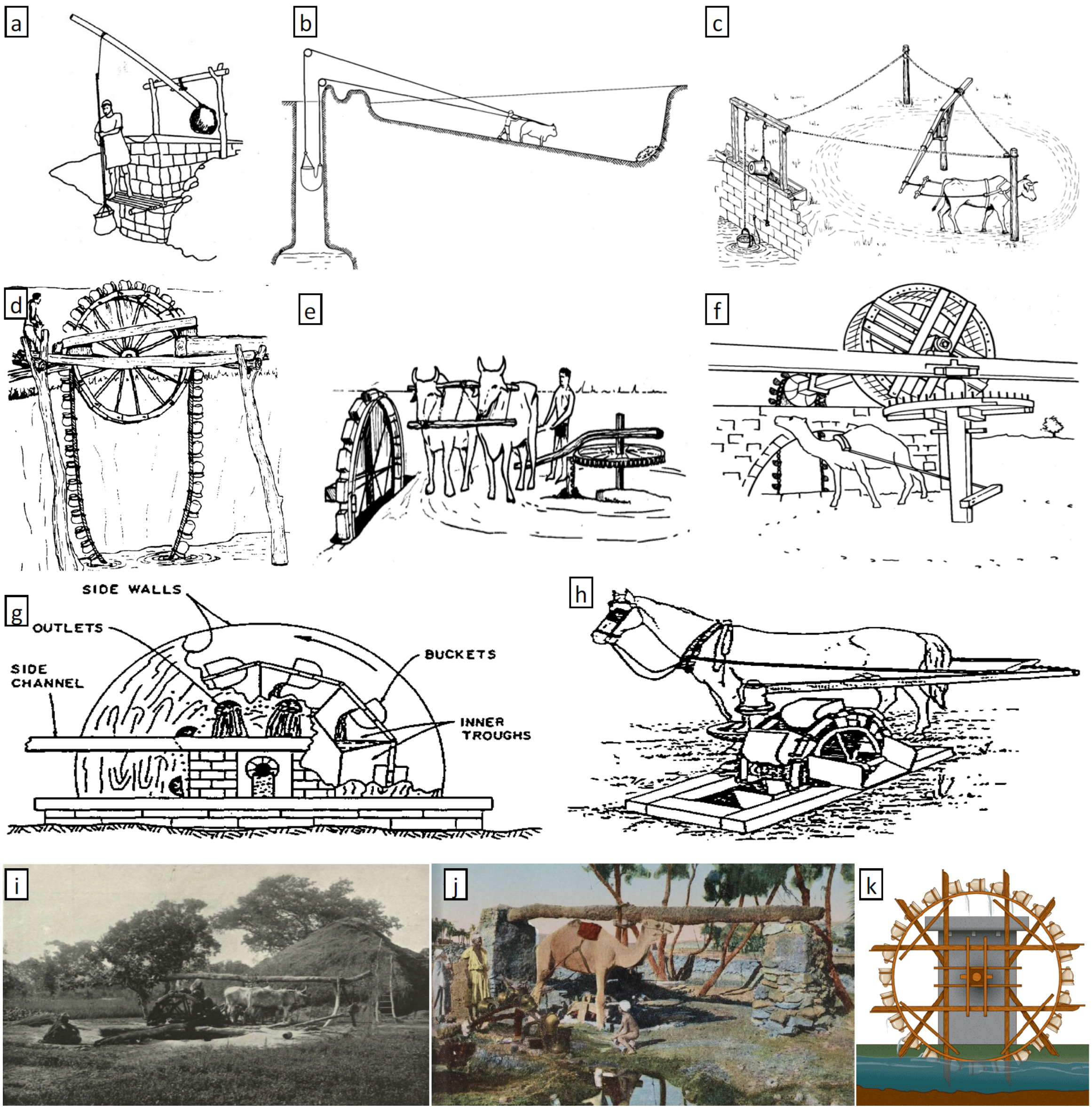


Figure 5. Traditional water lifting devices in ancient Persia, (**a**) Persian shaduf; (**b**) cross-section view of a mohte; (**c**) circular mohte utilizing two buckets with flap-valves in bottom; (**d**) Persian waterwheel; (**e**) a bullock-driven Persian waterwheel of the conventional chain and bucket type; (**f**) camel-driven Persian waterwheel showing over-head drive mechanism; (**g**) modified Persian waterwheel or zawafa; (**h**) zawafa by horse power; (**i**) improved Persian waterwheel or sakkia; (**j**) sakkia by camel power; (**k**) Persian *Noria* (adapted from [30,31,33–36]).

Traditional wooden Persian waterwheels were fitted with earthenware water containers, but a variety of all-metal, improved Persian waterwheels have also been built. Metal Persian waterwheels could be made smaller in diameter; this reduced the extra height the water needed to be lifted to, before being tipped out of the containers. The required well diameter was also reduced. A modified version of the Persian waterwheel (called the zawafa, zawaffa or jhallar) includes internal buckets within the waterwheel drive, which catch the water and direct it through holes on the side plate, near the hub, into a collection trough (Figure 5g,h). This reduces both the splashing and spillage losses and the extra height above the collection channel at which the water is tipped [33]. Roberts and Singh [35] stated that a modernized metal Persian waterwheel, of 153 m^3/h capacity lifted through 0.75 m. This implies that efficiencies as high as 75% are possible with modernized devices, which are rather good.

An advancement over devices that used a cyclic procedure (*i.e.*, filling a container with water, dumping the water, and then repeating the cycle) was the development of devices that scooped and emptied water in a continuous motion. The sakkia (sakia or saquiyah), introduced by the Persian Empire *ca.* 500 BC, used animal power to turn a waterwheel or chain that had numerous, evenly-spaced buckets attached (Figure 5i,j). At the lowest point, the buckets were filled with water, which were then emptied at the highest level. The sakkias are still in use today. The other device was the Persian Noria *ca.* 200 BC (see Figure 5k and [27,31,37]). Traditional forms of pumps in ancient Persia are shown in Figure 5.

3. Early Chinese Dynasties

The shaduf in China is known as *Jiégāo* and was locally called Diaogan, as well. According to the Agricultural Books of Ancient China written by Wang Zhen (1271–1368), Yi Yin invented the *Jiégāo* in the first year of the Shang Dynasty (*ca.* 16th–11th centuries BC) [38]. A wooden pole with a 2.6 m long, tapering body and circular ends was found at the site of an ancient copper mine in Ruichang of Jiangxi Province in 1988. There is a round arch groove at a distance of 1.66 m from the thin end of the pole. The pole was considered as the beam of *Jiégāo* and the groove would be the notch or mortise, cut into the beam to articulate the upright post like a hinge.

Archaeological studies showed that the Ruichang's copper mining had started from the Western Zhou Dynasty (*ca.* 11th centuries–771 BC) ([20] p.47). The results indicate that the *Jiégāo* had been invented and used widely in this Dynasty. Historical records further support this conclusion. For example, the earliest record of the *Jiégāo* is a quoted passage between Yan Yuan *(ca*. 521–490 BC) and Shi Jin in Chapter five of Chuang Tzu [39]. A pictorial stone of the Han Dynasty (*ca*. 206 BC–220 AD) describes a water lifting scenario with the *Jiégāo*, a device similar to the shaduf (Figure 1). The pictorial stone was made in 147 AD and is now stored in the Han Wuliang Ancestral Temples in Jiaxiang County of Shandong Province.

Hùdǒu was another common water lifting device in ancient China (Figure 6). It consists of ropes and a container. Two ropes are fastened symmetrically at the top edges of the container, which is a wooden bucket or a wicker basket. Two persons stood face-to-face and pulled on the ropes. The container, filled with water, would be lifted successfully from wells or rivers. An oblate wooden bucket with double square poles at its edges was found on the site of Gaocheng city (21st–11th centuries BC) in Hebei Province [40].

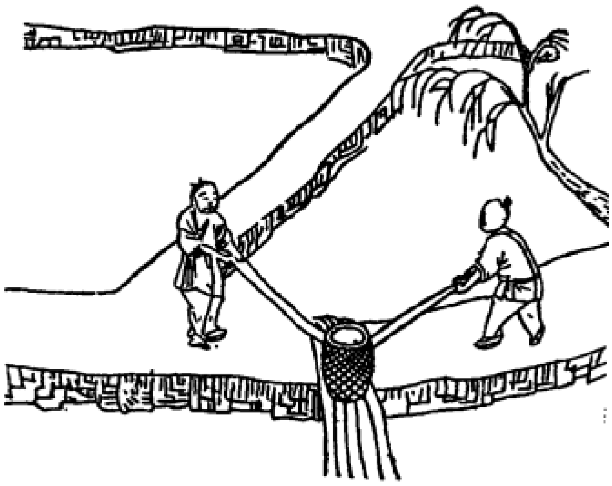


Figure 6. Schematic illustration of water lifting scenario with the *Hùdǒu* [40].

The *Lùlu* was a groundwater lifting device in ancient China. It consisted of a wooden stand, a wheel an axle, a hand crank, and ropes. The wheel axle was the most important component. A wooden wheel axle was found on the site of Tonglvshan ancient mine in Dazhi County of Hubei Province in 1973. Studies showed that it was a component of *Lùlu* used to raise mined ore and water from lower levels, during the Periods of Spring and Autumn and Warring States (771–221 BC) [40]. The wooden wheel axle is the first material evidence for the *Lùlu* up to now. Many pictorial stones of the Han Dynasty describe the water lifting scenario with the *Lùlu* (Figure 7). This suggests that the *Lùlu* was used widely in everyday life and for farm irrigation.

Figure 7. A wooden wheel axle of the *Lùlu* at the site of Tonglvshan ancient mine ([20] p.58).

The *Lùlu* solved the problem of water lifting from deep wells. This marked a new epoch in the development and utilization of groundwater. With a series of technical innovations during the Ming and Qing Dynasties (1368–1911), the *Lùlu* gradually became the most usual groundwater lifting device in the north of China. Innovations included replacement of manpower by horsepower, the introduction of multiple containers and an increase in the depth of the well. The *Lùlu* is still used nowadays in rural areas.

In most cases, the *Jiégāo*, *Hùdǒu*, and *Lùlu* were used to lift water from wells or near rivers. There are lots of rivers and streams in the south of China. A water lifting device called locally *Jījí* was invented for water delivery over a distance. The *Jījí* was actually a river version of *Lùlu* and could be adjusted for stretching far into the distance with large level differences. It was described by Liu Yuxi (772–842) ([20] p.58). According to historical records, its basic principle is demonstrated in Figure 8.

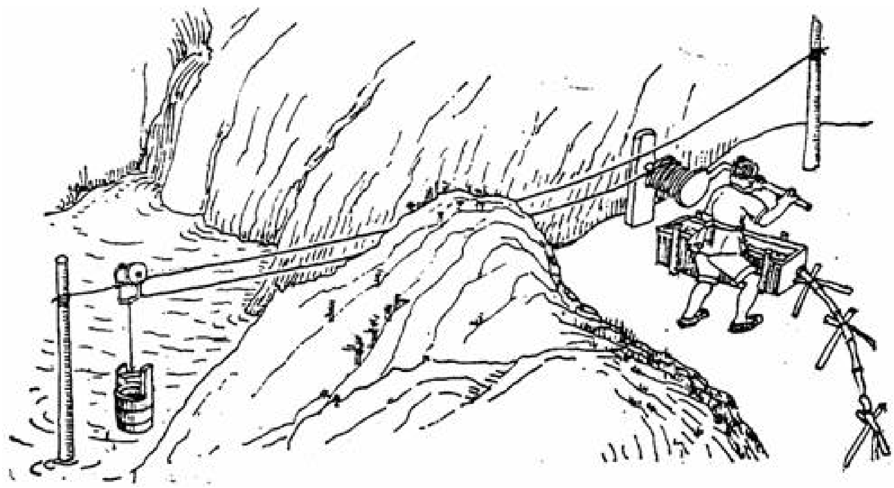


Figure 8. A sketch of *Jījí* [40].

4. Historical Times

4.1. Classical and Hellenistic Periods (ca. 480–67 BC)

The hydraulic endless screw of Archimedes (287–212 BC), which was described, but not necessarily invented, by the Hellenic mathematician and engineer [11], is a mechanical device, which is used for lifting water. Lazos (1999) [11] reported that several ancient Historians, e.g., Vitruvius (*ca.* 80–20 BC), Stravon (*ca.* 63 BC–23 AD), Philon of Byzantium (*ca.* 280–220 BC), and Philon of Alexandria (*ca.* 20 BC–50 AD), considered that it was indeed invented by Archimedes. The invention of this device is still an open discussion. Some bass relieves in the palace of Sennacherib (king of Assyria, 705–681 BC) at Nineveh and literary references would suggest that the water screw was possible used in Mesopotamia several centuries before the time of Archimedes [41].

It consists of a wooden shaft with convolution (curves) made of thin and flexible willow or wicker branches (one stuck on the top of the other) so that a screw is created. The screw is rotated within a wooden pipe. The device is placed in the water with a typical slope of 30 degrees (Figure 9). By rotating the screw the water trapped within its coils is lifted towards the upper end of the pipe. The Archimedes screw is the first known type of displacement pump [10,42].

The Archimedes screw has been widely used over the centuries [43]. Especially, it has been used to raise irrigation water and for land drainage and has been often powered by people or animals. This device, besides being of simple construction, has the additional advantage of being able to transport water that contains mud, sand, or gravel and is still used today for example to raise the return activated sludge so that it can be recirculated to the inflow of a wastewater treatment plant by gravity [11].

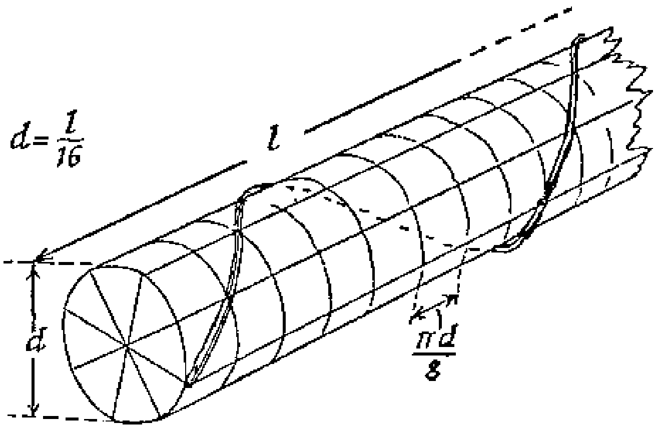


Figure 9. Design of the endless screw of Archimedes based on the description of Vitruvius (adapted from [44]).

Athenaeus in his treatise *Δειπνοσοφιστές* states [45,46]:

Περί δέ της υπό Ιέρωνος του Συρακοσίου κατασκευασθείσης νεώς, ης και Αρχιμήδης ην ο γεωμέτρης επόπτης, ουκ άξιον είναι κρίνω σιωπήσαι, σύγγραμμα εκδόντος Μοσχίωνός τινος, ω ου παρέργως ενέτυχον υπογυίως. Γράφει ουν ο Μοσχίων ούτως: '(...) Αρχιμήδης ο μηχανικός μόνος αυτό κατήγαγε δι' ολίγων σωμάτων. Κατασκευάσας γάρ έλικα, τό τηλικούτον σκάφος εις τήν θάλασσαν κατήγαγε. Πρώτος δ' Αρχιμήδης εύρε τήν της έλικος κατασκευήν'.

This roughly translates as follows: *As far as the ship constructed by Ieron the Syracussian is concerned, which was overseen by Archimedes as the overseeing geometrician, I think that I should not omit mentioning the writing of someone named Moschion. He mentions: Archimedes the engineer alone succeeded this with little help. Through the construction of a helix, he managed to bring down such a ship to the sea. Archimedes was the first to invent this construction of the helix.*

An elegant device, which might be used for many functions, as for example for lifting water from rivers to higher places (water gardens and farms), is presented in Figure 10. It was probably invented by Philon of Byzantium (*ca.* 280–220 BC) as reported by Oleson [23] and Lazos [47]. This device can be used in a strong current flowing downhill, which is copious enough in relation to the water which this device lifts. It consists of a rectangular building similar to a tower. A trench is cut from the river up to the tower. The proportions of the tower are such that it is not structurally weakened by its height. A wooden floor is placed on the tower foundations, resting on masonry and the water directed over it. The tower is dispatched to a certain distance from the river bank, so that the mass of water in the river could not enter the area from which water is collected. The front and the back part of the tower should be spaced, so that this construction is restricted to the place where the water is drawn. It is set up on a very solid cross-shaft, an axle which carries pulley wheels. Each end of the axle is clad, and fitted into a square bearing member presenting a socket in which it can turn easily. Another solid axle is placed on the upper part of the tower, similar to that in its lower part. The irrigation wheel is in the middle of this axle. At each end of the two axles identical pulley wheels are attached.

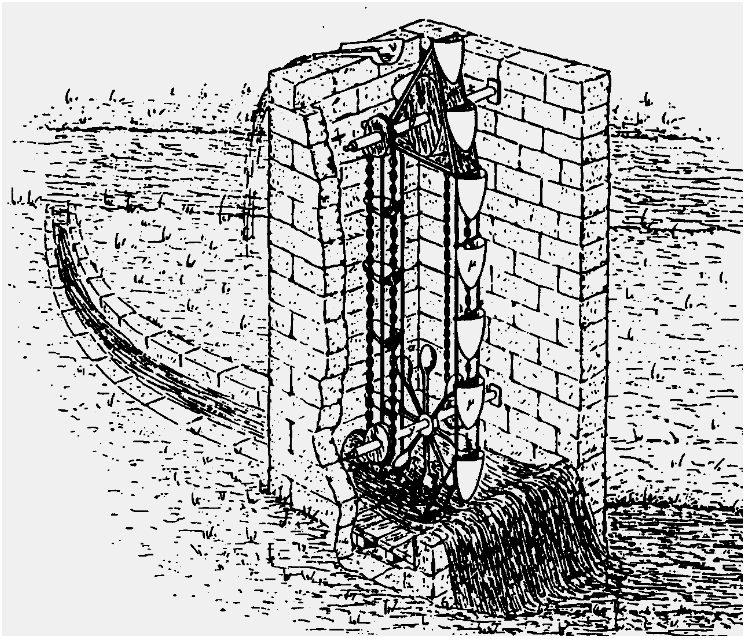


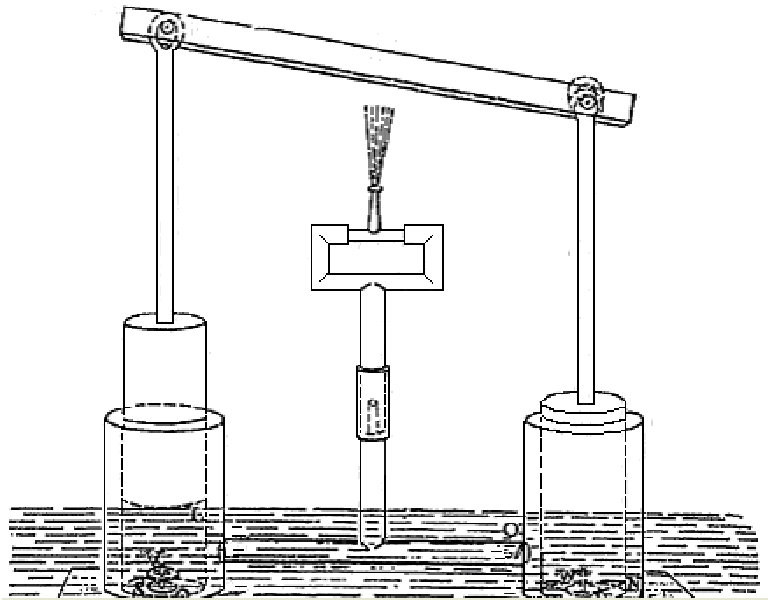
Figure 10. Philon's paddle-wheel driven bucket-chain (adapted from [48]).

Another lifting mechanism, the force pump, was invented by the engineer (initially barber) Ktesivius (or Ktesibios or Tesibius) of Alexandria (*ca.* 285–222 BC). The force pump has been described by Heron of Alexandria (*ca.* 10–70 AD), Mathematician and Engineer, in his book *Pneumatica*, I 28, who is considered the greatest experimenter of antiquity, *the Da Vinci of antiquity*. In addition, it has been described by Philon Byzantius (*Pneumatica*) and Vitruvius (X 7, 1–3). This pump consists of two cylinders with pistons that were moved by means of connecting rods attached to opposite ends of a single lever [49]. The force pump was used in many applications, such as in wells for pumping water, in boats for bilge-water pumping, for basement pumping, in mining, fire extinguishing, and water jets [50].

Ktesivius invented the bellow before inventing his pump [51]. It was an ingenious mechanism consisted of a cylindrical leather bellow with a wooden ringed frame. At the base, it had a heavy lead disc with leather-made non-return valves and at the top, a wooden lid with the outflow pipe incorporated in it. It functioned with the reciprocating movement of the pivoted lever, which was connected to the flow pipe of the bellow. The bellow was sinking into the well, and water was entering the valves of its lead disc.

Unfortunately, Ktesivius's writings have not survived, and his inventions are known only from references of Vitruvius, Heron of Alexandria, and Philon of Byzantium (*ca.* 230 BC). In addition, Ktesivius's work was further improved by Vitruvius, Philon of Byzantium, and Heron of Alexandria [10,52]. The principle of the force pump is rather simple. Water is allowed to flow through a one-way valve into a cylinder and then it is pushed out by the action of a piston, through another one-way valve into a delivery pipe (Figure 11a,b).

(**a**)



(**b**)

Figure 11. Ktesivius force pump as described by: (**a**) Philon; and (**b**) Heron with adjustable nozzle (adapted from [52] and [53] respectively).

4.2. Roman Period

Ktesivius' piston-type pump was used for the supply of air to the Hydraulis, the first known musical instrument *harmonium*, which is considered as the first organ [49]. It was also invented by Ktesivius. The Hydraulis consisted of two air-supplied Ktesivius' pumps, the *pnigeus* by which the air pressure was regulated, the keyboard, and the musical pipes (Figure 12a,b).

Another lifting device, the chain pump was invented in Hellenistic Alexandria by the engineer Philon of Byzantium. This consisted of a set of pots attached to a chain or belt that was moved by a rotating waterwheel [50]. The chain pump is a type of water lifting in which several circular discs are positioned on an endless chain. One part of the chain dips into the water, and the chain runs through a tube, slightly bigger than the diameter of the discs. As the chain is drawn up the tube, water becomes trapped between the discs and is lifted to and discharged at the top [10].

Several devices, including the organ (*harmonium*), have been invented by Heron of Alexandria. Most of them were based on the siphon principle, or more generally, the combined action of air and water pressure. Ktesivius, Philon Byzantius, and Heron of Alexandria were the three most famous engineers of Hellenistic Alexandria, whose studies mark a significant progress in hydraulics. This progress allowed installation of advanced water supply systems like that of the Pergamon citadel, in which pressure pipes (probably made of metal) were implemented [50].

(**a**) (**b**)

Figure 12. The Ktesivius' Hydraulis—Fragmentary hydraulics with 19 bronze tubes from the 1st century BC: (**a**) from Museum at Dion in north Hellas (adapted from [54]); and (**b**) reconstruction of hydraulic organ at Weissenburg in Bayern (adapted from [55]).

Other types of water lifting devices which were also used for irrigation in the Helenistic years were various types of *tympana* (with fixed blades and capacity of about 30 m^3·water/h) [8]. The magical fountain was invented by Heron of Alexandria (*ca.* 10–70 AD), an ancient Hellenic mathematician and engineer, who was active in his native city of Hellenistic Alexandria, Egypt. It was a most brilliant fountain, which shot water higher than the available level of its reservoir, defying ostensibly the hydrostatic pressure. It consisted of one open and two airtight containers placed one above the other (Figure 13). The middle airtight container was filled with water and a pipette started a little above its bottom and led to a nozzle above the upper open container. When water was poured into the upper open container, it flowed through a pipe, into the lower airtight container [49]. The confined air in this lower container was pressed and it displaced the water of the middle container through another pipe, forcing it to rise to the nozzle and to form a small spurt. The spurt of water supplemented the water of the upper open container (maintaining the level constant). Thus, this process was self-supporting and it continued automatically until all the water from the middle container was emptied (Heron of Alexandria, *Pneumatics*).

Heron described the construction of the aeolipile (a version of which is known as Heron's engine) which was a rocket-like reaction engine and the first-recorded steam engine. Heron's aeolopile is shown in Figure 14. It was created almost two millennia before the industrial revolution [56]. Tassios [57] supports that the aeolipile was mechanically combined to the Ktesivius pump, known as the first steam water pump on earth.

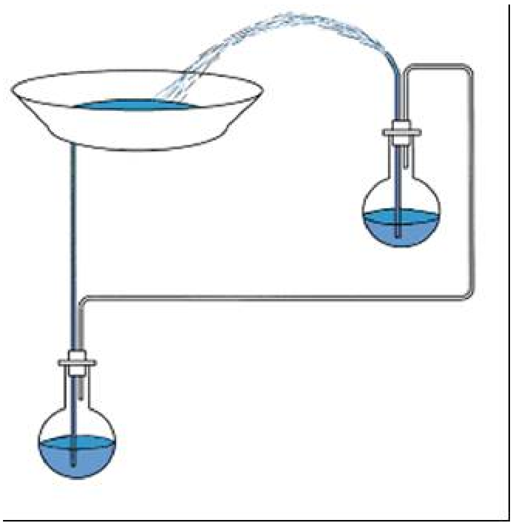


Figure 13. The magic fountain of Heron (Adapted from [49]).

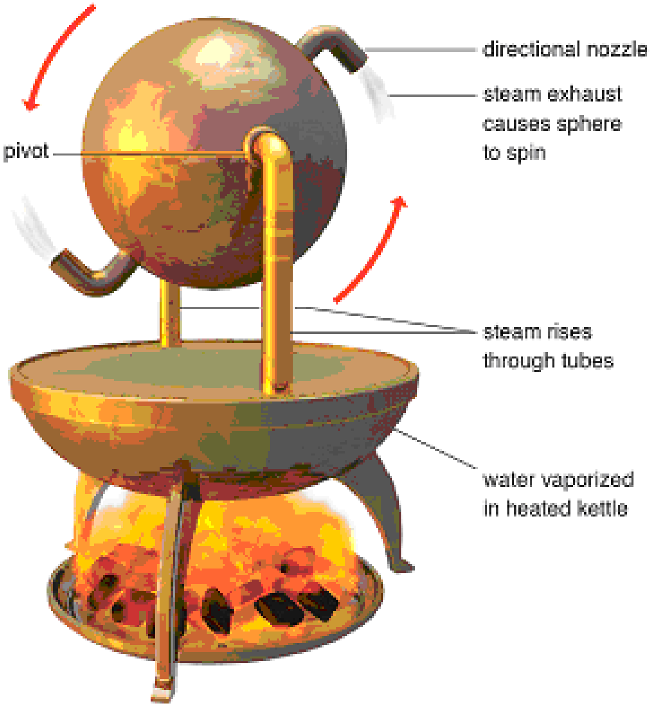


Figure 14. Heron's aeolopile [58].

In addition, chain pumps were used for centuries in the Roman times in the Mediterranean region and in Europe. Such pumps were also used in ancient China by at least the 1st century AD. In China, they were called *dragon backbones*. One of the earliest accounts was a description by the Han Dynasty philosopher Wang Chong around 80 AD [59].

5. Late Chinese Dynasties

By the 2nd century AD, during the Han Dynasty, the Chinese also used chain pumps that lifted water from lower elevation to higher elevation. These were powered by manual foot pedals, hydraulic waterwheels, or rotating mechanical waterwheels pulled by oxen. The water was used for public works of water supply for urban residential quarters and palace gardens, but mostly for irrigation of farmland canals and channels in the fields [59]. The *dragon backbones* is suitable for lifting water 1–2 m. During the Tang and Song dynasties (618–1270), the *dragon backbones* were most widely used in irrigation, drainage, and water supply. Three different sketches by Song Yingxing from the Ming Dynasty are shown in Figure 15 [40].

(**a**) (**b**) (**c**)

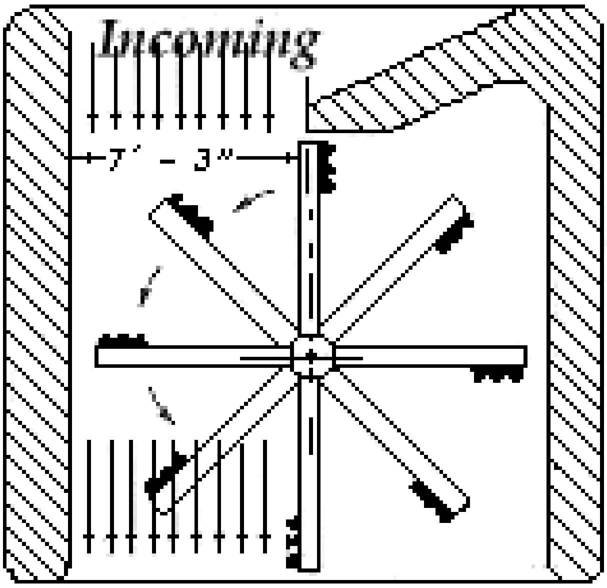
Figure 15. Three types of *Dragon backbones* during the Tang and Song dynasties: (**a**) hand-operated; (**b**) foot operated; and (**c**) oxen powered [40].

6. Byzantine Period and Venetian Rule (*ca.* 330–1600 AD)

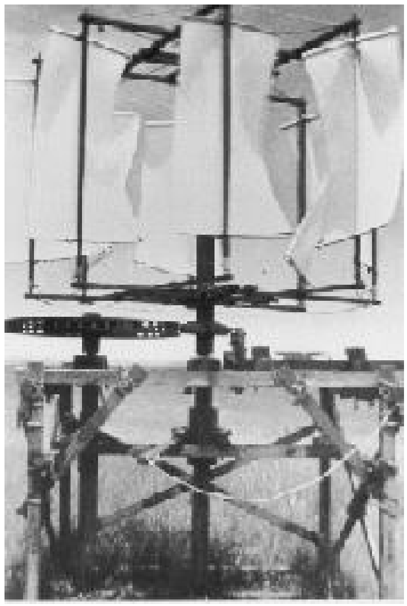
The first windmills were developed in order to automate the tasks of grain-grinding and water-pumping and the earliest-known design is the vertical-axis system developed in Persia *ca*. 500–900 AD. The first use was apparently for water pumping, but the exact method of water transport is not known, because no drawings or designs—only verbal accounts—are available. The first known documented design is that of a Persian windmill. It had vertical sails made of bundles of reeds or wood, which were attached to a central vertical shaft by horizontal struts (Figure 16a). A 19th Century American approximation of this panemone device is shown in Figure 16b.

Vertical-axis windmills were also used in China, often claimed as their birthplace. While the belief that the windmill was invented in China more than 2000 years ago is widespread and may be accurate, the earliest actual documentation of a Chinese windmill was in the 12th century during the Ming Dynasty [60] by the Chinese statesman Yehlu Chhu-Tshai [61]. Here, also, the primary applications were apparently grain grinding and water pumping [52]. Wind-driven waterwheels were used in ancient Tibet and China since the fourth century [62].

It has been claimed that the Babylonian emperor Hammurabi planned to use wind power for his ambitious irrigation project in the seventeenth century BC [63]. One of the most scenic and successful applications of wind power (and one that still exists) is the extensive use of water pumping machines. A very vivid example of this is to be found in the island of Crete. Here, even today, literally hundreds of sail-rotor windmills pump water for crops and livestock (Figure 17).



(**a**)



(**b**)

Figure 16. The Persian panemone: (**a**) A design of the Persian panemone; and (**b**) A 19th-century American approximation (adapted from [61]).

Figure 17. Water pumping sail-wing machines in the plateau of Lassithi in the Island of Crete (adapted from [64]).

In India, during the Mughal period (*ca.* early 15th–late 18th century), the introduction of the Persian waterwheel and the use of animal power increased the sustainability and the availability of irrigated areas, particularly in the Punjab state, located in the northwestern part of the country.

The first windmills to appear in Western Europe were of the horizontal-axis configuration. The reason for the sudden evolution from the vertical-axis Persian design approach is unknown, but the fact that the European waterwheels also had a horizontal-axis configuration, and apparently served as the technological model for the early windmills, may provide part of the answer. Another reason may have been the higher structural efficiency of drag-type horizontal machines over drag-type vertical machines, which lose up to one half of their rotor collection area due to shielding requirements. The first illustrations (1270 AD) show a four-bladed mill, mounted on a central post, which was already fairly technologically advanced relative to the Persian mills. These mills used wooden cog-and-ring gears to translate the motion of the horizontal shaft to vertical movement to turn a grindstone. This gear was apparently adapted for use on post mills from the horizontal-axis waterwheel developed by Vitruvius [61].

The piston pump made its first appearance in the writings of Mariano di Jacopo (1382–1453), alias Mariano Taccola, an Italian engineer who was considered a forerunner of Leonardo da Vinci. This piston pump [47] had a suction pipe incorporated in it [65,66]. In 1580, the sliding vane pump was invented, followed shortly thereafter by the gear pump.

The piston vacuum pump would come along in 1650. It consisted of a piston and an air gun cylinder with two-way flaps and was invented in 1650 by von Guericke, a German scientist and politician. Also, the "plunger pump" was invented in 1675 by Sir Samuel Morland (1625–1695), a notable English 17th century academic and mathematician. He patented a *plunger pump* capable of raising large quantities of water with far less effort than that required by a Chain pump or other pumps known at that time [67].

The earliest evidence of chain pumps is found in a Babylonian text from about 700 BC [56]. However, as already mentioned, this was reinvented by Philon Byzantius, in the Hellenistic period and was used by the Romans and others.

Ibn Ismail ibn al-Razzaz al-Jazari (1136–1206 AD) was an important Arab Muslim scholar, astronomer, inventor and mechanical engineer from al-Jazira, Mesopotamia. Al-Jazari invented five machines for raising water, as well as watermills and waterwheels with cams on their axle used to operate automata, in the *ca*. 12th and 13th centuries, and described them in 1206 [68]. It was in these water-raising machines that he introduced his most important ideas and components (Figure 18).

The piston pump invented by Ktesivius was improved by many others and has the advantage that it will lift water to any height, consistent with the pump and the delivery pipe being able to withstand the hydrostatic pressure. However, it has significant drawbacks. First, the pumping mechanism is submerged in water; and second, if the water-level falls, the cylinder will not fill. The solution to these problems lies in the use of a suction pipe on the inlet of the pump. Not only does the suction pipe allow the pump to be placed above the water; it also accommodates changes in the water level. In theory, the suction stage can be as high as 10 m, the height to which atmospheric pressure will support a column of water, but in practice, 7.62 m is the maximum height of water lift.

A few years after the initial experiment on vacuum by Gasparo Berti, around 1640 the first vacuum pumps were created by Otto von Guericke the Burgomaster of Magdeburg. This is when the history of vacuum devices begins [69].

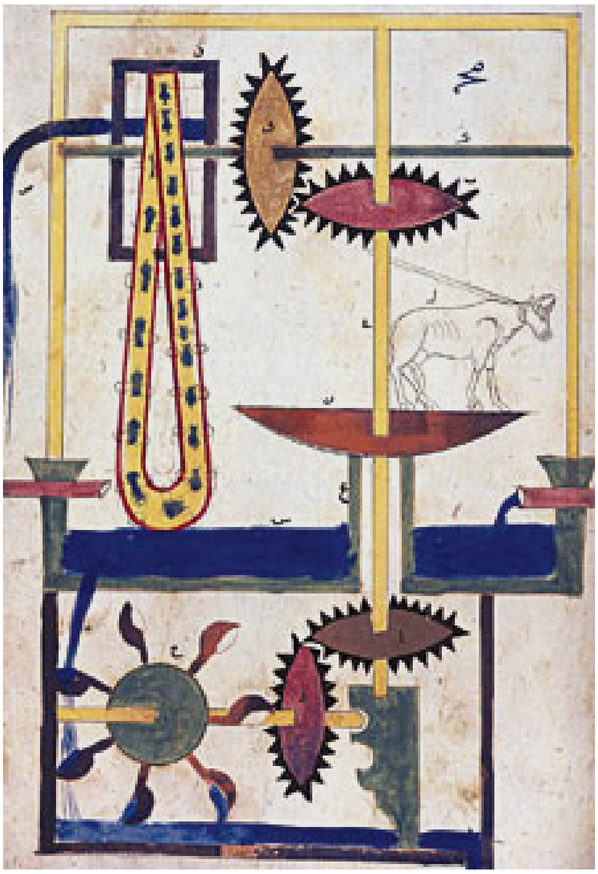


Figure 18. Al-Jazari's hydropowered saqiya chain pump device (adapted from [70]).

7. Pre-Columbian America

There is no evidence that water pumps or other water-lifting devices were known in pre-Columbian America, not even in the largest empires such as the Incas in South America or the Aztecas, Mayas and others in Mesoamerica. There is a misleading report made by the Spanish soldier and chronicler Pedro de Cieza de León (*ca.* 1518–1554), who reported to have seen pumps during his travel to the highlands of current Colombia in the Chapter XXXV of *La Crónica del Perú* (*the Chronicle of Peru*). Cieza de León found rivers with *very singular water* (*ríos de agua muy singular*), having salty water on the bottom and fresh water above them ([71] p. 387). According to Cieza de León, the natives used a kind of ship pump ("bomba de navío") made of hollowed thick reeds to extract the salty water, without mixing it with the fresh one. However, Rydén [72] compares this description to extract brine with those employed by other Indians of South America, concluding that Cieza de León mistook the device due to its shape. The way that natives extracted the brine was by introducing a pipe and when it reached the bottom of the river, they extracted water from the top end of the pipe with a small pot (the fresh water first, which was followed by the salty one). Thus, Rydén [72] emphatically concludes that *the pump must have been unknown to the South American Indians in pre-Columbian times*. There are no chronicles with descriptions of water devices in Meso-America, allowing us to extend Rydén's conclusion to the north of the continent.

8. Modern Times

At the end of the 18th century, a breakthrough was provided when James Watt invented the steam engine. In the 19th century, the production of thermal and electric motors, and the rapid development of industry and urban population growth posed problems, the solution of which was impossible without the use of pumps. At this time, the manufacturing of pumps became an important industry, and its value only increased over time, continuously seeking ways to improve the performance of pumps and to make these devices more reliable, efficient and economical [73].

Nowadays, piston pumps, centrifugal devices and even vacuum pumps open new horizons in water resources exploitation and management. Some of the main principles, however, indeed have their origins in antiquity. The main idea of using energy to increase the potential energy of water is still the same. Also, early pumping mechanisms, such as the Archimedes screw, represent the first paradigms of displacement pumps. In addition, the Archimedes' screw is only a characteristic paradigm, which justifies the significance and especially the durability and sustainability of ancient water technologies, throughout world history. These technologies are the underpinning of modern achievements in water sciences. It is the best proof that the past is the key for the future.

A series of Archimedes' water-screws in their modern form (in which the walls are not attached to the screw), as implemented in the waste water treatment plants (WWTPs) around the world. As an example, the pump station of WWTP in Bottrop, a city in west central Germany, on the Rhine-Herne Canal, which serves 1,350,000 e.p. (equivalent population), is shown in Figure 19. Its capacity is sufficient to successfully treat a catchment area of approximately 240 km^2 so, in addition to the Emscher water, it can also handle the household and industrial wastewater of four towns.

Figure 19. View of the pump station of the WWTP in Bottrop, Germany (by permission of A. N. Angelakis).

In the course of their missionary work, the catholic order of the Jesuits played an important role in the transmission of Western science and technology to China during the 17th and 18th century. Whilst their contributions to technology knowledge have been extensively investigated, their impact on hydraulics in China has received little attention so far [74]. A few illustrative examples of the application of Western hydraulic knowledge in China appeared with the publication of two specialized books with illustrations of hydraulic machinery, including the construction of a pumping station at the old Summer Palace in Beijing [74].

9. Epilogue

The search for effective technological solutions to water supply problems has a long history and has its origins in the prehistoric times. The marriage of technology with science and philosophy, which began in ancient Mesopotamia, Egypt, Hellas, China, and India, was an important advancement. The need of man to access water resources has always been a primary issue, not only in order to ensure survival, but also to improve quality of life. Pumping indeed enabled the development of settlements in locations that were not sustainable in the ancient times. Securing water supply for the population in a city, but also the development of agriculture depended highly on the ability to transport water over long distances and uphill, working against gravity.

The need to draw, transport and distribute water by overcoming the forces of friction and gravity found its solution in the various forms of pumps (water lifting devices). The required energy to overcome these forces was naturally provided by manpower (manual pumping), animals and the exploitation of the forces of nature (wind and water flow). The early mechanical pumps were simple, but also indeed ingenious devices that permitted the use of naturally available energy sources to bring about the desired task of water transportation and lifting. Several milestones were set through the history, from Minoan, Egyptian, Chinese, and Persian shadufs and the Archimedes screw to the modern piston and vacuum pumps, proving once again the ingenuity of man. The Industrial Revolution (the invention of the steam engine and the development of electrical motors) brought about new possibilities and performances, through the use of chemical and electrical energy forms, but modern pumps are still based on the first concepts as far as their mechanical principles of operation are concerned. Indeed, modern day centrifugal and displacement pumps clearly have their origin in the ancient concepts and designs [64]. The main difference lies in the manner of providing the required energy.

Many ancient civilizations, such as the Egyptian, the Persian, the Indian and the Chinese have sought technological solutions to water lifting and transportation. In assessing the history of pumping and water transportation we have to rely on archaeological findings and historical records. The lack of historical records limits, of course, our understanding of the availability of these technologies in some ancient cultures, such as the pre-Columbian America.

Our examination of the various technologies used worldwide clearly shows that there are many similarities in the methods and technologies used by the various ancient civilization. In many cases, it is an impossible task to delineate where and by whom a particular technology was first invented. As it is well known, the ancient Hellenic Culture is considered the birthplace of Western civilisation about 4000 years ago. The contributions of the ancient Hellenes to the fields of democracy, sciences, philosophy, art, architecture and history are without doubt unrivalled and still influence the lives of people.

Specifically, the ancient Hellenic technology first developed *ca.* 5th century BC, has continued up to and including the Roman period, and beyond. Concerning hydraulic technology, the ancient Hellenes, through their travelling and commerce, came in contact with and assimilated the techniques of other civilisations, developed them further and invented with great ingenuity new ones, such as the famous machines of the 3rd century BC, like the hydraulic screw, the rotary mill, the screw press, bronze casting techniques, the hydraulic clock, water organ, and many others. These inventions constitute today the building blocks of our modern technology, the development of which would be doubtful without them. The exploration of this age demonstrates how much more (than we believe) the modern western technological civilisation owes to the Hellenic one. Apparently, ideas, technologies, and practices developed during most of the Hellenic civilizations greatly influenced our modern technological knowledge; as Will Durant (1939) put it: *Excepting machinery, there is hardly anything secular in our culture that does not come from Hellas* [75].

It should be noted that although the use of modern pumps can help to improve water supply and to extend irrigated agriculture in the world, extreme extraction of groundwater also represents a serious threat to sustainable development. Abuse of pump power and new technology are shown in the cartoon of Figure 20 [76]. As shown, although high capacity pumping due to the use of electric power in place of hand-pumps has brought about more fertile lands the neighbor farmers were excluded from minimum water sources to irrigate their lands, while they blame the government for the situation. This cartoon presents clearly the challenges of modern technologies and the key role of both government and farmers for the proper use of pumps and other water lifting devices to achieve sustainable development.

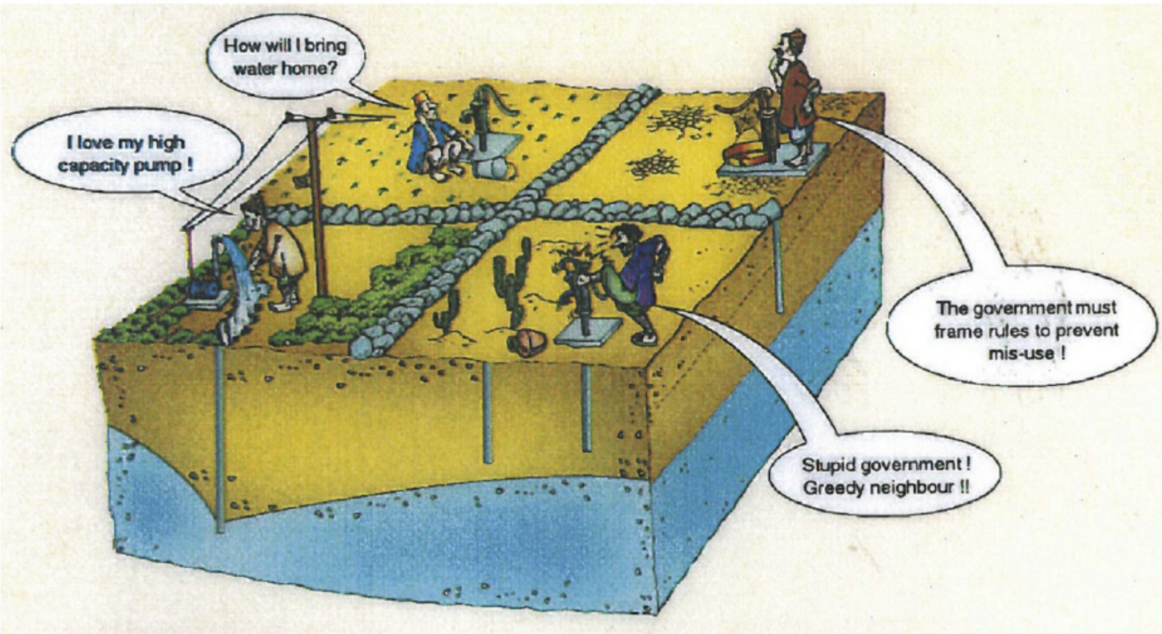


Figure 20. Misuse of modern pumps (adapted from [76]).

Technology has the same age as mankind. From antiquity up to the present day, most technological innovations were spread or disappeared in response to the needs and the commercial prospects of facilitating human life. In our days, technology is a complex social enterprise that includes not only research, design, and crafts but also finance, manufacturing, management, labour, marketing, and maintenance.

The demand for water lifting technology for meeting drinking, food production and domestic needs is very strong in the poor countries of the third world. In these countries, water lifting technologies find limited application due to a combination of technical, economic and social reasons. Some evident reasons are the required capital and operating costs and the complete lack of support services for maintenance. Probably, most small farmers seek safety and stick to familiar and readily available technologies, for which help, advice and spare parts are unnecessary or readily available and risks are minimized. However, if everyone followed this mentality, new and perhaps eventually better technologies would never become available.

Therefore, governments, international aid agencies and institutions have to take initiatives for the future development of small-scale agriculture. Moreover, they must assume the risks in this area on behalf of local farmers and test and demonstrate any technologies that appear promising in the local irrigation context. In most of the poorer developing countries of the world, there are incentives for increasing agricultural production, which requires pumped irrigation. At the same time, there is an increasing need to find methods for energizing irrigation pumps that do not depend on imported oil and electricity.

There is indeed a possibility of combining old technologies with current technical knowledge and equipment. Fraenkel [33] pointed out that: *before looking for radical new water lifting techniques, there is also much scope for improving traditional and conventional pumping and water distribution methods*.

The wide range of options for providing power for pumping water include some traditional technologies (e.g., windmills, *etc.*) and some entirely new technologies owing their origins to very recent developments, such as solar photovoltaic powered pumps. Also, there are technologies which have been widely and successfully used in just one area, but which remain unknown and unused in other areas with similar climatic conditions. An example is the hydro-powered turbine pump, which has been used extensively (tens of thousands) solely in China [33]. The waterwheel technology was improved to a fine art, until the time of the Industrial Revolution. The efficiency of waterwheels has approached 70% [77].

It is a fact that ancient pumping technologies are still in use today in several parts of the developing world. Research priorities should be undertaken towards the development of cost-effective approaches and practises, based on modernizing low-cost historical waterlifting technologies, through the replacement of muscle power (human or animal) by natural sources of energy. This is possible as a result of the recent technological progress in the renewable energy sector. A good paradigm is coming from the Hellenistic times, when Heron of Alexandria replaced muscle power for operating the lever of the Hydraulis (Water organ) by wind energy [57]. Another example is the adaptation of the traditional water wheel, which is a simple construction for use with renewable energy sources, providing thus a sustainable solution to meeting the water needs for rural agricultural development.

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Author Contributions

Stavros I. Yannopoulos prepared the manuscript and made mainly the Hellenic and Roman data collection; Gerasimos Lyberatos made the review of it, English corrections, and contributed to manuscript preparation; Nicolaos Theodossiou analyzed the data and codified the methodology; Wang Li collected and analyzed the data for the Asian civilization, Mohammad Valipour collected and analyzed the data for the Persian civilization as well as the challenges of misuse of modern pumps; Aldo Tamburrino collected and analyzed mainly the data for the Pre Columbian American times; and Andreas N. Angelakis had the original idea and supervised the research.

Conflicts of Interest

The authors declare no conflict of interest.

Appendix

Timeline for Historical Development of Water Pumps.

4000–3000 BC	Early uses of water power was used for irrigation in Mesopotamia
2500–2000 BC	Minoans invented the shaduf
2000 BC	Egyptians invented the shaduf
1200–800 BC	Early use of gravity fed as water lifting in ancient Persia (Qanat, collection of roof rainfall from roof, and horizontal well)
1600 BC	Chinese invented the *Jiégāo* (Chinese shaduf).
800–200 BC	Other methods for water pumping in Persian Empire (Persian shaduf, mohte, Persian wheel, zawafa, sakkia, and Persian Noria)
287–212 BC	Archimedes the famous Syracusan scientist and engineer invented the water screw
285–222 BC	The engineer Ktesivius of Alexandria (initially barber) has invented the force pump
260–180 BC	In Hellenistic Alexandria Philon Byzantius has invented the chain pump
200 BC	Waterwheel with pots attached or with compartments for the water
1200 AD	Chinese invented windmill for irrigation
1698 AD	Thomas Avery invented a pump that operated on steam to create a vacuum to draw water.
1580	Sliding vane pump invented by Ramelli; Serviere invents the gear pump
1650	Otto van Guericke invents his piston vacuum pump
1674	Sir Samuel Morland patents the packed plunger pump
1687	Denis Papin, French inventor, develops the first true centrifugal pump, one with straight vanes used for local drainage
1738	Ural hydraulic machinery plant established
	Plenty Ltd established
1790	Thomas Simpson establishes his pump business in London.
	Hayward Tyler established
1830	Screw pump invented by Revillion

1840	Henry R. Worthington invents the first direct-acting steam pump
1851	John Gwynne files his first centrifugal pump patent
1857	Henry R. Worthington produces the first horizontal, duplex, direct-acting steam pumps for boiler feed.
1860	Allweiler founded—A.S. Cameron invents the first reciprocating stream pump
1870	Osborne Reynolds, UK Prof., develops an original design of a centrifugal pump
1874	Charles Barnes of New Brunswick invents the vane pump
1897	Preston K. Wood makes the first deep well turbine pump in Los Angeles, California
1899	Robert Blackmer invents rotary vane pump technology, a pump design that was an important departure from the old gear principle and predecessor to today's sliding vane pumps.
1901	Byron Jackson develops the first deep well vertical turbine pump
1905	Multistage centrifugal pumps are developed
1908	Hayward Tyler creates its first electric motor for use under water and develops the wet stator motor for use as a boiler circulation glandless motor-pump
1916	Aldrich produces the first direct motor-driven reciprocating pump
1923	Ruthman Companies designs the world's first sealless vertical pump
1927	Aldrich produces the first variable stroke multi-cylinder reciprocating pump
1940	Axial-flow and jet pumps have been used as compressors in jet engines. Jet pumps are used in wells that are deeper than 60.69 m.
1956	Flygt introduces the submersible sewage pump

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