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Palaeo-Environmental Condition Factor on the Diffusion of Ancient Water Technologies

Summary

Thales of Miletus wisely declared that water is the vital element for life. Being the core substance for human survival, the management of water has always been an important matter. Early attempts to improve water-lifting devices for agricultural endeavors have been detected in Hellenistic Alexandria. However, aside from the limitations of the different devices, variations in geology also limit the use of some of these machines in specific areas. Some of these devices were used daily, whereas others remained impractical or were of minor importance due to their complicated nature, and some were even forgotten until they were later rediscovered. Water also became a basic power source, providing energy, e.g. for cutting stone or milling grain, and such applications constituted the first attempts at Roman industrialization.

Keywords: ancient water technologies; Hellenistic science; diffusion; geology; geography; Roman; aqueduct

Bereits Thales von Milet erklärte Wasser zum wichtigsten Element allen Lebens. Entsprechend kam dem Management dieser Ressource schon immer große Bedeutung zu. Erste Versuche, Wasser-Hebesysteme in der Landwirtschaft einzusetzen, lassen sich im Hellenistischen Alexandria nachweisen. Die Nutzbarkeit solcher Hebesysteme war eingeschränkt einerseits durch ihre individuelle Konstruktion, andererseits durch die Geologie vor Ort. Während dabei einige dieser Wasser-Hebesysteme täglichen Einsatz fanden, blieben andere ungenutzt oder gerieten auf Grund ihrer geringen Bedeutung oder ihrer Komplexität bis zu ihrer Wiederentdeckung in Vergessenheit. Wasser wurde damals auch als Energiequelle eingesetzt, wie zum Beispiel beim Schneiden von Steinen oder beim Mahlen von Korn. Solche Anwendungen stellen gleichsam den Anfang der antiken römischen Industrialisierung dar.

Keywords: antike Wasserstrukturen; Hellenistische Wissenschaft; Diffusion; Geologie; Geographie; römisch; Wasserleitung

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If only there is water, there will be life… and water always finds its way. (G. S.)

1 The short history of human adaptation to nature

The history of the relationship between *Homo sapiens* and the nature in which they lived, was reshaped about 10 000 years ago during the Holocene period. A constantly growing population in North Africa made it necessary for the people to develop a reliable water supply for multiple needs, such as preparing agricultural lands to provide food for the people. One of the first places where the transition from hunting-gathering to cultivation happened was the Middle East, about 10 000 to 9 000 BP. Thereafter, Central Europe began cultivation, with a delay of at least a thousand years, due to severe cooling periods and a strong advance of glaciers. This transition period, from nomadic to farming, was a fruitful turning point for *Homo sapiens*, since it created food security and stopped the long tradition of following wild herds.

Global warming during the Holocene finally opened the way for building advanced civilizations. At the onset of the Holocene, nomadic hunters started to build fixed settlements where water management was necessary. They benefited from the power of the available natural resources.[1] The traces of the structures of these fixed settlements can be found associated with irrigation and drainage channels in the Near East and early mining sites. Subsequently, gravity driven aqueducts and water and animal driven mechanisms were invented to provide bathing facilities and increase food production to satisfy the growing human population.

The first more advanced civilization formed during the mid-Holocene period was called the Atlantic; this was a warm and long period that provided the foundation for the development of the complex human cultures of the Phoenicians, Carthaginians, Greeks, and finally the Romans.[2] This is also the time when enhanced task-division was first apparent, making life easier, as people worked by means of a division of labor, working as merchants, soldiers, engineers, and craftsmen.[3]

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[1] Roberts 2014.

[2] Perry and Hsu 2000.

[3] Behringer 2009.

The techniques used to make tools were improved and, subsequently, people started to use these tools in their daily life. Seafaring was improved through the development of wooden sailing ships to make discoveries overseas. This brought together new ideas and technologies that people had observed in foreign lands during their travels. This travel also helped to build cultural connections and trade while climatic conditions were stable. Aside from trading goods such as ivory, pottery, and wine, the people also observed how those from different lands dealt with water and land management issues on a daily basis. After the first optimistic and unsatisfactory attempts to use these same technologies in their own areas, the people began to realize that some things worked differently in other geographical settings; this was the decisive point where innovation processes took place and different types of machinery and structures were constructed.

First, building a waterproofed cistern or digging a well in a private garden became a common and simple way of solving the water problems of individual citizens, although the latter required a technique to lift the water to the ground level, where the water was needed. Meanwhile, others had the idea to transport water over short distances via conduits, which was followed by the tapping of water sources from even further away by opening channels and constructing tunnels or building high-level bridges with channels or pipes. Early examples include the Minoan Aqueducts of Crete, the aqueduct of archaic Samos with the famous Eupalinus Tunnel, and Athens and Syracuse and the aqueducts and well-houses of Megara.[4] The technique of building aqueducts was not very common until the Roman era, since it was quite an expensive solution, even though it involved water being driven in a natural way by gravity, without any additional labor. In most cases, well or cistern technology fulfilled the daily needs of the people, although the simple lifting mechanism of a bucket and rope system did not always answer their needs, since in some areas, a well could be more than 90 m deep. Therefore, this practical way of obtaining a regular water supply had to be improved through the innovation of water-lifting techniques, which are discussed in this contribution.

2 Hellenistic science, technology, and the first attempts to diffuse them

Looking at history, it is curious that most of the ancient large civilizations emerged at about the same latitude: the Mediterranean, Mesopotamia, Iran, China, and India, and in the southern hemisphere, Peru. The most common aspect of all these countries was a climate that was not overwhelmingly hot, nor one with a cold Nordic atmosphere.

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[4] Angelakis, Savvakis, and Charalampakis 2007; Kienast 1995; Koutsoyiannis et al. 2008; Crouch 1993; Tölle-Kastenbein 1990.

The favorable conditions of having a moderate climate and fertile land led local people to be at the center of the technological improvements connected to irrigation. Presumably for this reason, Hellenistic Alexandria was the birthplace of important scientific innovations.

The Alexandrian school of engineers in Hellenistic Egypt triggered a breakthrough in natural philosophy between the 3rd and 1st century BC. Early scientists were encouraged to concentrate on the development of mechanisms to lift great masses, resulting in lever, pulley, and cogged wheel systems being developed, and the invention of the first practical equipment to increase the harvest.

In fact, Egyptians triggered the first agricultural work in the Nile Valley. This may have been driven by a sudden population increase, the largest human population in any area until that time, and growing based on the controlled use of the clay-rich, abundant water of the Nile.[5]

Meanwhile, in another Hellenistic city, Syracuse, the inventor of many theorems and practical devices, Archimedes (287–212 BC), was working along the same lines to understand how things work in nature. Although his invention of the catapult was relatively destructive in the hand of others, the common use of the *Archimedian screw* he developed is a good example of his lasting inventions.

Two additional Greek engineers worth mentioning by name are Ctesibius (285–222 BC) and Heron of Alexandria (AD 10–70), who are known until today as the fathers of pneumatics. Nevertheless, their inventions, such as water-clocks, a steam-powered engine, and an automatic door opener, were not practically used for a long time. They were also criticized by many scholars of their time as being nothing more than toys to entertain and amuse the public.[6] The early written sources on the lever and pulley system demonstrated their use in daily life,[7] but scholars did not show the same attention to Hero's (Heron of Alexandria) labor saving cogged wheel mechanism perhaps because it was not used widely for some time. The force-pump, however, is an exception that after several modifications was distinguished from other inventions by being a life-saving device that was utilized as a fire-extinguisher and also for its practical application in lifting water to a higher elevation. Otherwise, most of these first inventions of Greek engineers from the Alexandrian School were either only locally in use or seen as nothing more than scientific experiments.

The innovation process of the force-pump and many other mechanisms was not a coincidence; it coincided with the date when the Romans started to create written records of history. The Romans ruled the Mediterranean region for more than five hundred years and made great improvements in all aspects of life; therefore, some big

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[5] Butzer 1976, 76–92.

[6] Granger 1931.

[7] Pleket 1967, 39–40.

changes took place in the practical use of the inventions mentioned above. Starting from this point, diffusion of the machines increased consciously by the Romans, who improved these machines, allowing them to shift from only purely scientific inventions to becoming applied devices in their time. However, why and how Romans became involved in the diffusion of water technology is a curious issue that needs to be examined in order to understand the needs of the people of that time and ancient trade policies.

Plato (427–347 BC), in his *De Re Publica,* indicated that "love of money" was a characteristic of the Phoenicians and Egyptians. This was seen as the main difference they had from the Greeks, who were seen as having a "love of knowledge".[8] The love of making money might have also been a dominant character of the Romans and their trade policies. Certainly, the contribution of Romans to technology and engineering issues was mainly in the field of practical application.[9] During the Roman era, not only practical technologies were in common use, additionally, entertainment machines were well diffused and available almost everywhere throughout the Empire. They were a top request of Roman nobles and land owners for their new villas, such as a force-pump to spray a water jet from a pool to where they were reclining and dining on couches to impress their guest, or raising water for their gardens or opening a temple door automatically, using the principle of Hero's pneumatics. These devices played an important role in showing Roman prosperity to the rest of the world, and led others to admire the Roman lifestyle. More importantly, the diffusion process and common use of water technologies was part of the growing Roman economy. A number of waterwheel remains from mining sites in Hispania, Britannia, and Dacia and the watermill complexes for grinding flour to provide *annonae*, proved their common application for industrial use. The Roman military played a powerful role in the diffusion of ancient water technologies and the widespread use of water-powered machines by means of their strong military organization and colonial administration.[10]

In the following, I discuss these technologies and the important features that played a role in their diffusion, other than the palaeo-environmental conditions.

3 Comparison of ancient water technologies

3.1 Water-lifting devices

People needed to raise water for various applications. Water-lifting was indispensable for mining sites and for extinguishing fires. After simply digging wells to reach the ground-

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[8] Griffith 2000.

[9] Landels 2000.

[10] Spain 2002, 51.

water level, people constructed a rope and bucket as the first mechanism for lifting water to the surface level. However, as wells got deeper, more efficient devices were needed as deeper wells would require longer ropes, which were in turn much heavier, resulting in it being much more laborious to obtain water from the deeper wells. Several types of water-lifting devices were invented, which are compared below.

3.1.1 Shādūf

The device known as *shādūf* in Arabic, *kelōneion* in Greek, is also called *tolleno* or *swipe.* It is one of the simplest and earliest water-lifting systems, and was invented even earlier than the Hellenistic period, during the Early Bronze Age. It is still in use in Egypt and many areas in North Africa and the Middle East today. This crude mechanism involves only a bucket, or something similar to a bag, and a rope; however, it is different from a bucket-rope arrangement, as it also includes a heavy counterbalance bound to a wooden arm and a supporting skeleton. There are no historical remains at the archaeological sites, due to its perishable nature, but there are illustrations of the *shādūf* on frescoes, mosaics, and vases; e.g., the example of a wall painting from Thebes, depicting the use of a *shādūf* from 1300 BC.[11] This system was not an ambitious one, but was rather modest in nature, and was only meant to raise water from a river or a ditch for agricultural purpose. The *shādūf* is a low-lift device, but nevertheless has a relatively high discharge volume, providing up to 6 m^3/hour at a height of 3 m.[12]

The biggest advantage of the *shādūf* is its low-cost and simple nature. It can also raise water from narrow shafts, and this made it one of the most practical devices available for lifting water. However, the *shādūf* can only raise water over short distances due to the limited height of its beam, and its capacity is also low compared to other water lifting mechanisms.[13]

3.1.2 Waterwheels with a compartmented body (tympanum or tympanon/drum) and compartmented rim

Waterwheel technologies were powered by natural resources, such as water, wind, animals, or manpower. The *tympanum or tympanon* (drum) in Greek is the oldest known complex water-lifting mechanism, which even inspired Archimedes in his invention of the water-screw.[14] It was a machine composed of a closed wheel with openings that allowed water to enter at the bottom of the wheel and let it escape again at the top. The Latin word *tympanum* was first mentioned in *De Architectura* by Vitruvius (70–15 BC) as

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[11] Oleson 2008, 350.

[12] Oleson 1984, 369.

[13] Oleson 2000, 227.

[14] Oleson 1984, 298.

a device to lift water for irrigation purposes or for supplying the needs of salt works.[15] It is clear that the *tympanum* has a few advantages over *Archimedes' screw,* due to the simplicity of its construction; however, it is only able to lift water to a height of two thirds of the wheel's diameter, limiting its use. Another disadvantage was related to problems with clogging. Additionally, its torque was not as efficient as that of the water-screw.

The waterwheel, with its compartmented rim, was a similar mechanism to the *tympanum,* but using the rim of the wheel only. Waterwheels were first mentioned in Apollonius' treatise (262–190 BC) of about 240 BC.[16] The invention of both types of waterwheel, with compartmented rim and body, dates back to the mid-third century BC. The earliest known evidence of an animal-driven wheel for lifting water was at Perachora, Greece from the 3rd century BC.

3.1.3 Water-screw or cochlias (Archimedean screw)

The water-screw can be found under the name *cochlias* in Greek literature. It was allegedly invented especially for one area, the Nile Delta and its surrounding terrain, and is known as the Egyptian or *Archimedean screw* (*tambour*), since its invention during the 3rd century BC is mostly credited to Archimedes (Fig. 1). Some scholars believe that it was already in use before Archimedes' visit to Egypt, but he saw its value and worked on a design to improve it for the needs of the Egyptian farmers. It has a quite simple construction: a large helix open at both ends in a cylinder with water scooped at the end of the helix. It was low-lift, with a constant rise, but still effective and easy to handle. Moreover, its most important advantage in comparison with the force-pump or *tympanum* was its low susceptibility to clogging, which is a real problem in the Nile Delta, where alluvium-rich fields with solid matter such as mud, sand, silt, and gravel were subject to draining. Aside from these considerable advantages, a high level of friction reduced the efficiency of the water-screw. The advantage of raising quite large amounts of water was overshadowed by its low-lift nature – not as high as a waterwheel – which limits its use in some fields.

Archaeological finds and textural sources indicate that the screw was used for irrigation purposes, mostly in Egypt, along with draining water from mines and dewatering bilge-water from ships. The earliest known evidence for its use in a ship was a screw designed by Archimedes for Hieron II of Syracuse in the third century BC.

On the map of diffusion of water technologies, we can see widespread use of the water-screw in Spanish mines, due to its capacity to assist in effective drainage (Fig. 2). Posidonius (135–51 BC) noted that it can drain a great amount of water with relatively minor labor.[17] Although most examples date back to the Imperial Age, a depiction of

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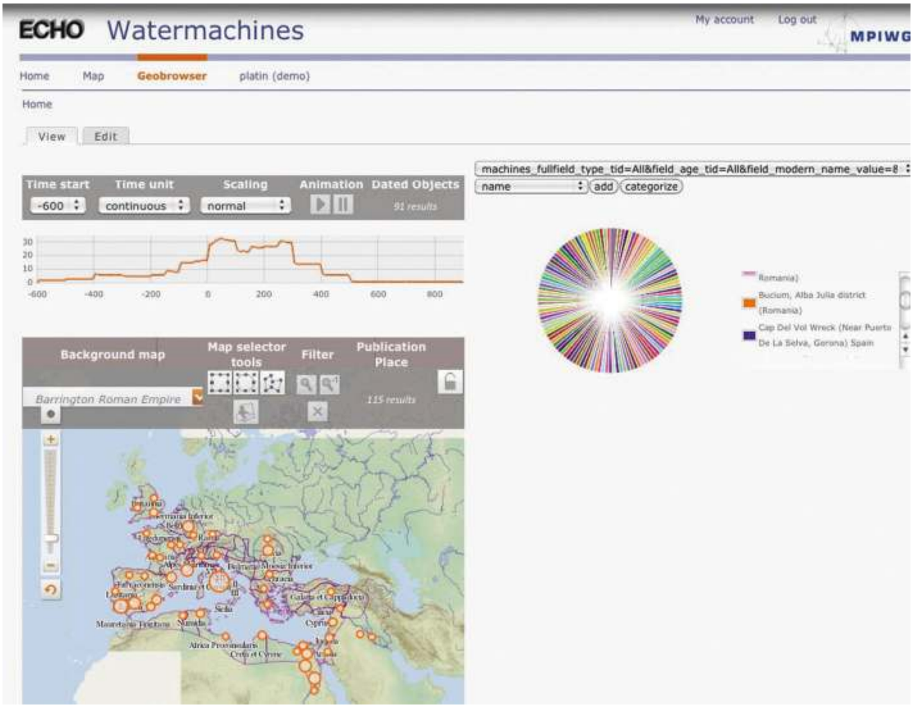
[15] Oleson 1984, 113.

[16] Wilson 2002, 7.

[17] Oleson 1984, 89.

Fig. 1 A reconstructed *Archimedean screw* in Israel. This low-lift device has the advantage of draining quite a reasonable amount of water by a simple manual system. In antiquity, the device was turned with the feet. Photograph and reconstruction work, Yeshu Dray.



machines_fullfield_type_tid=All&field_age_tid=All&field_modern_name_value=8
name

Time start: -600
Time unit: continuous
Scaling: normal
91 results

Background map: Barrington Roman Empire
115 results

Fig. 2 Diffusion map of water machines for lifting and draining water and providing power for milling activities. The database is online and has a dynamic map that covers the Mediterranean and Western European examples.

Fig. 3 a) Wooden force-pump found in Bertrange, Luxembourg. The pump dates back to AD 270 and was found in the Roman fort. The original remains are in the National Museum of History and Art in Luxembourg. b) This example of a force-pump is made of bronze and was used in the Sotiel Coronada copper mine in southwest Spain, either as a fire-extinguisher or to spray cold water on rocks to fragment them. This force-pump dates back to the Imperial Roman period and is housed at the National Archaeological Museum in Madrid.

one water-screw operating on Egyptian agricultural land was found in the Casa dell' Efebo, Pompeii, proving its use before AD 79.[18] Another screw from Ciudad Real was discovered in a mining site in Spain that dates back to the post-Roman period.

3.1.4 Force-pump

Vitruvius' comment in his treatise *De Architectura* on, "useless objects that flattered the senses by amusing the eye and ear",[19] was most likely a criticism of the water-organ or similar *automata* mechanisms. However, when he describes all the water-lifting machines in his treatise, he provides a separate chapter for force-pumps, emphasizing their practical use and clever invention by the Greek engineer Ctesibius of Alexandria (Fig. 3). In fact, Vitruvius is the only scholar who attributed the invention of the force-pump to Ctesibius and, therefore, the device is referred to by some people as the *Ctesibica machina*. This exceptional machine is, "extremely useful and necessary", according to Vitruvius' account.[20]

Compared to all the others, the force-pump was the most advanced water-lifting mechanism. The mechanism was originally made of bronze and consisted of pistons working in two vertical cylinders connected by transverse pipes that led pressurized water to a central delivery pipe. The water was locked in under the force of gravity by one-way valves at the base of the delivery pipe. The lower part of the pump was submerged into a water body. The literary sources mainly mentioned the bronze force-pump as a fire-extinguisher and it was used to spray fresh perfumed water during games in theaters

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[18] Oleson 1984, 241.

[19] Oleson 1984, 24.

[20] Oleson 1984, 124.

or amphitheaters, as it was a portable mechanism.[21] There are some rare examples, such as the bronze, portable pump from the Sotiel Coronado mine in Spain, which was used as a fire-extinguisher or, more interestingly, to spray a cold water stream on top of heated rocks to fragment them for mining.[22] These special applications were related to the advantageous features of the pump: being portable and also providing a jet of pressurized water.

There are some other recorded uses of the force-pump, e.g. for raising water for an orchard in a Roman villa and for kiln-production. Of all of the water machines, the force-pump had the most delicate nature and was relatively expensive to build and maintain. These features played an important role throughout its diffusion process to the provinces of the Roman Empire. Nevertheless, after the first century BC, some radical innovations established a new design where wood replaced the original bronze; this process helped the force-pump become more affordable and easier to produce and maintain. After this adaptation process, the force-pump became more widespread and appeared in several areas with several different applications, as a multitask machine for gardening and for raising drinking water from the wells in villas or on rich farms. Another advantage of this adaptation, was that the wooden apparatus was less affected by water than the bronze ones, and this led them to remain preserved at their original locations; broken bronze pumps could be recycled for their metal value, while broken wooden ones would have no value, and would be left in place. The 20 known examples from domestic areas are mostly wooden, but also include eleven bronze pumps and one lead example.[23]

The force-pump was also commonly used as a bilge-pump in ships after the 1st century AD. In fact, there were a number of other possibilities to drain bilge water from the hold of a ship, such as the *chain-pump* and water-screw. The *chain-pump* had properties of both bucket-chain and force-pump and consisted of a series of wooden disks on a rope that were pulled though a cylinder. This was allegedly more effective than the water-screw, since the screw might be handicapped by its low lift and required horizontal placement. The *chain-pump* also shared the same advantages of the *Archimedean screw*, in that it did not need any maintenance for cleaning muddy water and was more stable under the pitching and rolling conditions of the ship at sea than the screw installation.[24]

3.1.5 Bucket-wheel

The design of the bucket-wheel machine *(polykadia 'multi-bucket' in Greek)* was forgotten for centuries and only rediscovered in the Middle Ages. It is similar in its reappearance to the force-pumps.[25] It is known to be the simplest of the 'higher-head' devices. In contrast

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[21] Stein 2014, 21, 31.

[22] Stein 2014, 24.

[23] Stein 2014, 34–35.

[24] Wilson 2011, 42.

[25] Landels 2000, 67.

Fig. 4 Bucket-chain installation reconstructed for the Roman bath of the local inn at the Xanten archaeological site in the ancient Roman town of Colonia Ulpia Traiana in Northern Rhine-Westphalia.

to the previous devices, the bucket-wheel was apparently driven by animal power in Greek speaking communities in Egypt. The bucket wheel consists of a series of buckets fixed around the rim of a wheel. The buckets were probably wider at the bottom, so they could scoop up a reasonable amount of water and lift it to a narrow opening at the top level.[26]

3.1.6 Bucket-chain

The bucket-chain, or *halysis* in Greek, is another type of 'high-head' water-lifting mechanism, most likely the improved model of the bucket-wheel (Fig. 4). It consists of a tread-mill on a horizontal axle with two parallel endless chains where the buckets are fixed to the chains at relatively equal intervals. Since the buckets are bound to the chain and due to the elaborate nature of the iron-work, this device was likely to be more expensive to build than the bucket-wheel. However, in some places where there was not

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[26] Landels 2000, 67.

enough space to build a bucket-wheel, it was a preferable device. The advantage of the device was related to its working principle being independent from its diameter. Moreover, the percentage of spillage was reduced to a minimum by the rapid turning of the buckets only after reaching the axle. Nevertheless, if the water amount was not high enough, there was the problem of the chain slipping around the axle due to the heavy weight of the chains and buckets.

It is most likely that the bucket-chain was used more often in small-scale settings, such as a villa or for a farm, where the water would be used for drinking, cleaning, and other needs of a household.

3.1.7 Noria (Egyptian wheel) and Sāqiya (Persian wheel) or wheels of pots

The word *sāqiya* is often used to describe a water-lifting mechanism using ceramic pots, although it actually refers not to a water-lifting machine but to the driving mechanism (*sāqiya* gear) that drove it, usually powered by an animal (Fig. 5).[27] The earliest known example is from Alexandria, in a fresco representation that dates back to the 2nd century BC.[28] It basically consists of a pair of cog-wheels oriented at right angles to one another, designed to transfer the rotation of a vertical shaft driven by an ox into a more easily applied horizontal motion. The *sāqiya* with a bucket-chain wheel was very common in Fayyum, Egypt. Several *sāqiya* examples were continuously in use for up to one hundred days along the Nile River, to irrigate farms outside the period of the annual Nile flood.

The *noria* has many similar features as the *sāqiya*, although it is usually driven by water-power. The gear-driven *noria* examples have a short shaft and were commonly used in the Iberian Peninsula and Morocco.[29] Its application was generally for irrigation purposes, just as the *sāqiya* was. The first known example of the *noria* is a representation of a mosaic in Apamea, Syria from the 2nd century AD.[30] Their common appearance in Spain, especially during the Arab conquest, may be due to their simplicity and efficiency, which helped their widespread distribution, resulting in their use becoming a tradition.[31] A nice example of a hydraulic *noria* is situated along the Orontes River near Hama, Syria[32] and another example from the Islamic period has recently been restored in Córdoba, Spain (Fig. 6).

3.1.8 Relations of water lifting devices

Like the *shādūf*, the *sāqiya* and *noria* are examples of relatively crude water machines. According to many scholars, their widespread distribution was related to their simplic-

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[27] Oleson 2000, 267–272.

[28] Oleson 1984, 382.

[29] Schiøler 1973.

[30] Oleson 2008, 42.

[31] Wilson 2003, 141.

[32] Oleson 2000, 236–238.

Fig. 5 A reconstructed medieval *sāqiya* example from Alcázar of Córdoba. This machine was powered by manpower to lift water from the cistern below, and was used to irrigate the garden.

Fig. 6 This typical example of a *noria* (water-wheel) was reconstructed on the Guadalquivir River in Córdoba. Possibly, it was originally built by the Romans and modified in medieval times to provide water for Alcázar de los Reyes Cristianos (a medieval castle) for gardening and for milling grain. This *noria* was powered by the river.

Fig. 7 An ideal deep rectangular shaft for a sizeable bucket-chain in Pompeii, the main installation for the Stabian Baths. The carbonate incrustations can be clearly seen along the left side wall. The original wheel driving the installation was positioned in the room behind the modern fence. The onset of the arc, visible in the back wall of the shaft, held the bucket chain installation.

ity.[33] They functioned according to the same principle, although the *noria* was driven by water-power, whereas the *sāqiya* was powered by an animal. The most practical feature of the *sāqiya* is its ease of use, even without practical knowledge. The large number of *sāqiya* and *noria* that were found in countries such as Egypt and Spain, and in North Africa shows that they were used in connection with agriculture, and indicates the ease with which they could be installed and used.

The bucket-chain, the most applied of all the water-lifting machines, raised water from deep shafts (wells); however, its large structure required a wide, usually rectangular space (Fig. 7). The compartmented waterwheels, the *noria* and *tympanum,* also required special room for their installation. These waterwheels were also some of the most commonly used machines to lift water. Here, however, the limitation was due to their structure, since the lower part of the wheel must be immersed in the water body to carry water to the higher level, which could not exceed the top of the wheel.[34] The same set-up is needed for a water-screw; placing its lower part within a water body limits the height to which water can be lifted. Therefore, unlike the force-pump and bucket-chain, they are unable to lift water from a narrow and deep shaft. Conversely, the force-pump had the disadvantage that it could only move small volumes of water, which limited its application; however, the biggest advantage of the force-pump was not only its ability to raise water from a deep and narrow shaft, but also that it could produce jets of water under pressure. This led it to be classified as a more ingenious but elaborate device than the other mechanisms, and expanded its application to be used as a fire-extinguisher or fresh water or perfume sprayer.[35]

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[33] Schiøler 1973.

[34] Oleson 1984.

[35] Stein 2014, 32.

3.2 Comparison of watermills

The invention of the watermill allowed converting the natural power of flowing water in order to utilize it for mechanical work. The idea of the watermill wheel was not different from the wheel used for raising a heavy volume of water to higher levels, and one may have influenced the other. Later on, however, the contribution of the watermill to establish the mass production of flour was a landmark for the advancement of the Roman economy. There were also other types of mechanical systems utilized; for example, quite simple ones like the trip-hammer, which work with the power of the water. There was no way to use the trip-hammer for continuous production; hence, it remained part of a small-scale farmer's economy.[36] The water-driven pestle was also an alternative way to pound and pull grain. Its common use in Italian provinces was pointed out by Pliny the Elder (NH 18.97). However, none of these methods were appropriate for a larger population and larger-scale production. Thankfully, the invention of the watermill, helped to solve the problem of discontinuity in mass production and it also helped to increase *per capita* productivity with its great output.[37] The similar shape of different watermill models may even mean that one was invented from the shape of the other. Two types of mills are briefly discussed below.

3.2.1 Norse and Greek mills (horizontal-wheeled mills)

The Norse and Greek mills were presumably simple, inefficient types of mills from a primitive model that involved low capital investment.[38] The biggest advantage of mills using the horizontal-wheeled system was the ease of construction, since there was no gearing involved. The water comes in as a jet with a very high speed and is used to turn the paddles via the sharp slope of the millrace or with a drop-tower installation for producing a fast water flow. The mills were commonly used in Northern Europe, in particular after the Middle Ages; the term 'Norse mill' presumably originated from its find location.[39] Since it is the simplest mechanism of the mills, it was probably invented as a first watermill mechanism, while the other types of watermills were probably derived from it.[40] It was not known to have been installed for industrial purposes, as no archaeological evidence has come to light yet.

The geographical setting played a crucial role when choosing a wheel type. Most examples of the horizontal-wheeled mills were located in areas with limited amounts of water, but also at locations where a high velocity jet of water could be produced by a sufficiently high hydraulic head, particularly in mountainous areas.[41] The known

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[36] Wikander 2000, 406–407.

[37] Wilson 2002, 30.

[38] Wikander 2000.

[39] Lucas 2006, 34.

[40] Wikander 2000, 395.

[41] Forbes 1964.

examples are mainly from the Southern and Eastern Mediterranean, such as Algeria, Palestine, Jordan, Naxos, and some others. These examples with drop-tower (*arubah*) installations, where water was stored at a higher level to provide pressurized water for turning the mills, were common in North Africa; a typical example is Oued Mellah in Algeria.[42] An example of a related type of mill (helix-turbine) from Roman times was found in Chemtou and Testour with a remarkably extended size, with three waterwheels at each mill, is worth mentioning.[43]

3.2.2 *Vertical wheel (undershot-overshot)*

The vertical wheel mill can only be used with a right-angled gearing system, which can convert the water-power from the vertical rotation of the mill wheel to the horizontal rotation needed for the millstones. Due to the complicated nature of the gear mechanism, it was probably developed later than the Norse (Greek) mills. There are some criteria that determine the type of vertical wheel to be used, overshot or undershot, such as meteorological, geological, and topographical conditions in the subject area. The overshot wheels can be optimal for a limited water supply and a high hydraulic head. For overshot mills, which are the most common types, an aqueduct that can provide water-power would have been the best option, since it can be easily regulated for maintenance work. Overshot mills were more efficient mills, although their construction needed much more work than undershot mills. Undershot mills are mostly fed by a river with a larger water supply and a lower head and are, therefore, easier to build, since there is no need for a hydraulic arrangement. However, they can only work when there is a strong and rapid water flow, such as from a river.

4 The role of geological settings and other factors on the diffusion of water technologies

A database was set-up in collaboration with the Excellence Cluster *Topoi* and the Max Planck Institute for the History of Science to see the geographical distribution of ancient water technologies. In the following section, the discussion concentrates mainly on the outcome of this “diffusion of the ancient water technologies” database, and the resulting interpretations.[44]

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[42] Wikander 2000, 377.

[43] Wilson 1995, 503.

[44] The “diffusion of the ancient water technologies” database can be visited under following link: https://drupal.mpiwg-berlin.mpg.de/watermachines/ (visited on 25/05/2018). The database has a dynamic map where the distribution of water machines is shown.

4.1 Water-lifting devices

The geological setting played a significant role in the diffusion process of water technologies and structures, and it is, therefore, surprising that it has not been discussed in detail before elsewhere. People were aware of natural resources and the importance of their power, like ores and water. This can be clearly seen if one looks at the ancient settlements of Greek colonies in Sicily or Italy. For example, the important settlements of ancient Athens (Greece), Nimes (Southern France), Syracuse (Sicily), and many others were chosen because they were especially close to springs where a perennial, continuous source of water was present;[45] even today, some of these sources are still in use. Greece is dominated by a limestone geology, where ancient Greeks benefited from groundwater sources, without needing to make investments to bring the water from greater distances, e.g. in Athens and Corinth. The main reason behind this choice was that a karstic system would not reflect the extreme seasonal variation in rainfall, since groundwater sources are generally well-mixed and provide a continuous water supply. Hence, Greek tribes also looked for a similar geological setting wherever they settled elsewhere. An example is Empúries in Northeast Spain, where the ancient Greek city was built on top of a karstic source, covering the people's water needs. In Sicily, the conditions were similar, in that Agrigento and Syracuse were located where Greek colonies benefited from the same type of karstic geology as found in their home towns, and they applied the same methods to supply water for their settlements.[46] The Greek founders of Syracuse originated from Corinth and specifically settled there due to the similar geology, climate, and natural water sources available in the cave settings. The geology of both areas consist of penetrable rocks that overlies a layer of impermeable clay, where Corinthians could benefit from their experience and know-how from their homeland, and could apply the same technologies here for water management. Therefore, until the population climbed up the hills of Syracuse, due to a significant growth of the city, people were satisfied with the water supply, only taking water from cisterns and wells, lifting the water by using simple lifting mechanisms and *hydrias*. There was, therefore, no need to build an aqueduct until the 3rd century BC.

Another factor that may have played a significant role in the diffusion process of water-lifting machines, suggested by a number of scholars, was the complexity of some machines that discouraged people of North Africa and the Middle East from using them in their daily life.[47] This might be one of the reasons that played a role in the widespread use of some of the crude machinery, such as the *sāqiya* and *shādūf* in these arid areas. Large-scale farming activities must have required a continuous production of water with

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[45] Crouch 1993, 71-72.

[46] Crouch 1993, 83–90, 96–99.

[47] Murphey 1951.

Fig. 8 Wooden fragments of the large tread wheel with compartmented rim from the Rio Tinto copper mine from Huelva, Spain. The water-wheel was used to drain water from the mine site. The water-wheel dates back to the 1st to 2nd century AD. It is presently displayed in the British Museum, London.

minimal expense and the lack of a water source to feed a gravitational aqueduct supply in many semi-desert regions gave rise to the common use of these simple machines. Meanwhile, there are very few finds of mechanical irrigation systems in use in rural areas in Italy. This was probably due to the abundance of small farms, which were unable to carry the expense of organizing animal or manpower to power the water-lifting system and the system's maintenance.[48]

Another powerful and relatively expensive installation is the tread-wheel with a compartmented rim, driven by animal or manpower. These are located mostly in ore rich geological settings with lead, silver, and gold deposits, in mining areas where slave power was also available (Fig. 8).

Force-pumps were mostly found at archaeological sites in Western Europe, where precipitation is relatively abundant throughout the year. Even though water scarcity was never dramatic in these areas, most of the eighteen force-pumps found in the wells were defective, most likely due to the decreasing of the ground water level after years of drought.[49]

Although the more advanced devices were presumably invented at a very early age, their diffusion took a long time. There are three main factors behind this delay worth mentioning, though other factors should also be considered. The first factor might have been the expensive and laborious construction of machines such as the waterwheel and force-pump. Aside from the expense of building and installing those machines, operating them by means of slave or animal power added additional expenses, and postponed

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[48] Hodge 2002, 248.

[49] Stein 2014, 31.

their diffusion and widespread use. For many agricultural sites, it was not possible and often not necessary to incur such expenses due to the small size of the plots.

A second factor in the delay of diffusion was the complicated nature of some of the devices like the force-pump, which was temperamental in some ways and required a reasonable knowledge of the technology used. There was always a danger that it would stop working due to its complicated nature, and it was difficult to maintain and repair, something that was unlikely to be done by simple farmers without know-how.

The last, but not least, factor was the amount of water that could be lifted, which was relatively low for some mechanisms. Some of the technologies were limited in their capacity, with the total amount of water they could raise being related to their diameter, as with the *tympanum*.

4.2 Watermills

Another issue in taking advantage of natural sources is the application of water mills. Mills were used earlier than the Classical period but were especially common during the Roman era, when they became a part of early industrialization. The water machines that were driven by water-power required a reliable water source for economic profit, since the machinery could turn without interruption, with the added possibility to control the activity. Therefore, these water-powered machines were consciously located in geographical settings where the precipitation is almost year round, providing a continuous water source. Wikander, however, explains in a plausible way, that there was not really a geographical constraint on the diffusion of mills.[50] Indeed, in the Mediterranean, there seem to be many areas with reasonable sources that have a continuous water supply that would have been suitable for mills. Although no earlier watermill examples have yet been found by archaeologists, one well-known watermill for grinding flour was identified in Ephesos that dates back to the early Byzantine period, and a saw-mill was identified at Hierapolis that dates back to the 3rd century AD.[51] Both of these examples are from Asia Minor. It might, in fact, have been an even larger problem to obtain a water supply from the rivers of Western Europe, where there is usually a problem with flooding of the rivers, which might have caused an interruption in flour production and even damage to the installations. As a consequence, the limitation issue regarding environmental conditions should be regarded skeptically, taking poor archaeological remains into account.

Most examples of watermills for industrial use were overshot wheels that usually had a connection with a costly aqueduct supply; the water moved continuously through the

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[50] Wikander 2000, 378.

[51] Wikander 2000, 378.

Fig. 9 Undershot wheel installation of a reconstructed Byzantine water mill at the river Nahal Taninim. This structure is a good example of ancient water-mills that still function.

channels and chutes to the waterwheels, which turned the paddles. The Barbegal watermill complex in Southern France was one of the best examples of this kind of expensive and large-scale arrangement.[52] Being part of an ambitious setup, water machines driven by water-power from aqueducts needed to be located in a specific geographical setting, located on a top slope where aqueducts brought the water from a higher position to turn the wheels by gravity. Until today, some of the locations where overshot wheels were located in archaeological sites benefited from similar topographical setting for grinding flour as at Barbegal: the Janiculum,[53] the Baths of Caracalla in Rome,[54] Venafro,[55] Saepinum in Southern Italy,[56] and the Agora of Athens in Greece.[57] Fortunately, some of these watermill installations preserved their carbonate incrustations: this has helped researchers to determine the design and size of the watermill structures and to improve our understanding of the activities of these machines through their working period, such as their upkeep, which indirectly contributes to our knowledge of the Roman economy.[58]

The second type of watermill, the undershot wheel, also required a continuous water supply, although these mills could be located directly in rivers or streams where water could turn the paddles. Most present-day examples come from tidal rivers in England, where the current can move the paddles in both directions. The Mediterranean climate is a typical bimodal one, where rainfall amount varies quite dramatically throughout a year due to the only serious precipitation taking place during the winter. The lack of powerful perennial rivers in the Mediterranean basin, due to seasonal precipitation,

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[52] Leveau 2006; Sellin 1981; Hodge 1990.

[53] Wilson 2001.

[54] Schiøler and Wikander 1983.

[55] Reynolds 1983, 34.

[56] Guendon 2007.

[57] Parsons 1936.

[58] Sürmelihindi et al. 2018.

may have played a role in the paucity of undershot mills in this basin. A rare example consists of the Byzantine mills at Nahal Taninim in Israel (Fig. 9).

5 Adaptation processes

Ancient water mechanisms changed in nature as "one species turns into another", due to geographical advantages or disadvantages, analogous to "natural selection", as described by Charles Darwin (1809–1882), but driven deliberately by the people of that time. A number of adaptations were made by engineers or workers, to amend the disadvantages of some water-lifting devices, such as the wheels with compartmented rim and the force-pump, to make them more practical, cheaper, and finally, more applicable to people's needs and circumstances. For example, the wheel with compartmented rim was equipped with inexpensive pots, another innovation process helped increase the common use of the *sāqiya* in Egypt and North Africa as well. Probably between the 1st and 3rd centuries AD, terracotta pots replaced wooden buckets, since this was more affordable due to the local scarcity of wood.[59] Finally, for many waterwheel applications, it was a tradition to use available material for their construction. Therefore, the examples of terracotta pots found were generally from Egypt, whereas in Western Europe, wooden buckets were commonly in use.[60]

The force-pump was probably the most altered by innovation processes. The remains of all found force-pump examples from wells were wooden in design and, therefore, the adaptation process from bronze to wood most likely took place because bronze pumps could have decayed more easily under water and very quickly gone out of order. Here, the advantage was not only about making devices more practical, but also making them cheaper.

The three types of watermills discussed above, with three different designs, were chosen due to their functionality in their geographical location. The horizontal-wheeled mills were replaced by either overshot or undershot ones, due to their low level of water capacity in some areas.[61] Another study also discussed the more common use of undershot wheels, even though overshot ones were more efficient;[62] the reason for this lies in the availability of the geographical setting. The overshot mills required a large head (2–10 m) and were more often located in steep areas where supplementary construction was necessary, such as a millrace, pond and shaft, and sluice, which requires a significant patronage to finance the expenses. On the other hand, the advantages of undershot wheels were numerous, as they could operate with a low head of less than 2 m, which

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[59] Oleson 2008, 352–353.

[60] Wilson 2002.

[61] Wikander 2000, 378.

[62] Denny 2004.

made their diffusion more widely applicable and practical in areas close to the population centers, utilizing small brooks or streams in any flat area with a relatively less ambitious output.

6 Comparison of the factors of diffusion of aqueducts, *qanats*, and water-lifting devices

An aqueduct was a symbol for prosperity, a luxurious life, and a so-called 'civilized community.'[63] Public latrines and big bathhouses projects were difficult to build without economic support, and were a way of winning a large number of supporters and an important position or concrete power for a tyrant or an emperor. If one traces the locations of the Roman aqueducts, one can recognize their extensive distribution in the Western provinces of the Empire.[64] These provinces were Romanized over time, especially through Roman invasions. There is a general postulated opinion about the aqueducts in the Near East that these were built mainly for Roman soldiers to provide them with a Roman-approved life style, and not to attract the local population.[65] Natives of the invaded lands kept using their traditional technologies to raise water from wells and cisterns and to irrigate their land.[66]

There is a common underestimation of the nature and science perception of Graeco-Romans.[67] Hodge remarks, "[t]here is no evidence of any real or systematic geological understanding of the ancients".[68] Nevertheless, ancient Greeks consciously and successfully sought karstic locations for a place to settle. Such locations can easily be recognized due to the weathering of the limestone. Apparently, the Greeks knew about the presence of water in this setting, and probably also knew how to extract it.[69] There are several example sites that support this idea, but one well-known site is the Greek colony of Émpurias (Ampurias), Spain, where an installation, possibly a bucket-chain, lifted water for a bath.[70] This installation worked for a considerable time, as can be seen from the floor, which has carbonate incrustations from the carbonate-rich groundwater. This incrustation was due to the location of the ancient city on top of karstic geology, where there would have been enough water due to the abundant water storage in karstic caves under the city. Despite the growing population during the later Roman epoch, people never needed to build an aqueduct on this site.

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[63] Hodge 2002, 51.

[64] See for example www.romaq.org (last accessed 25/05/2018).

[65] Hodge 2002, 252.

[66] Wittfogel 1956.

[67] Hodge 2002, 51.

[68] Hodge 2002, 51.

[69] Crouch 1993, 83–99.

[70] Buxó 2008, 9–16.

The common distribution of *qanats* in the Middle East and North Africa were associated with specific geological settings too. Most desert regions in Syria and North Africa supported the widespread use of *qanats* because of the advantageous geological setting formed by impervious layers of calcium carbonate and quartz. Moreover, there is a strong correlation between the location of *qanat* sites with the amount of rainfall and evapotranspiration in relation to topography and geology.[71]

How force-pump installations were diffused is difficult to track because many bronze examples were likely recycled. One possible explanation for their seeming non-existence in the Near East is likely related to the unreliable climatic conditions where the groundwater level was subject to change. The representation of the *Archimedean screw* examples from Egypt maybe also provide proof that people of this time understood that the silty plains of the Nile Delta were not an ideal place to use delicate mechanisms such as a force-pump. Also, there were no mills with undershot wheel mechanisms, as the famous flooding of the Nile River might have destroyed a fixed installation.

7 Conclusions

The importance of population dynamics in the evolution of tool and machine technology is nowadays a well-accepted fact. The East African Rift Valley was a center of innovation because *Homo sapiens* populated this dry land, where the production of food and water was a primary concern. The breakthrough of scientific innovations and developments of water technologies during the 3rd century BC by Hellenistic scientists was driven by the Ptolemy Dynasty's desire to increase the food production and make advances in water management. However, some scientific inventions stemming from this time remained without a practical application for many centuries until the Romans came to power. The Romans triggered the advances that resulted in these devices being applicable to daily life, and also helped diffuse these technologies throughout the Empire, even involving the Roman army in their distribution. The diffusion process of water technologies not only helped the Romans to have more comfort in activities of every-day life but also brought about economic benefits through the trade of these machines. Although the diffused ancient water machines were well-developed and elaborate, people recognized some of the disadvantages and limitations of the different machines and how those related to the paleo-environmental conditions of the working areas. Therefore, especially in the ancient settlements of the Middle East and North Africa, people commonly continued using the same techniques from their own tradition that they had learned long ago from their ancestors, instead of applying new techniques.

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[71] Lightfoot 1996.

Moreover, some of the water-lifting devices, with their limited water capacity, remained small-scale applications and were never part of ambitious irrigation projects, as far as is known today. The best example of this are the force-pump installations.

Another disadvantage with a force-pump or a wheel with compartmented rim is that they were quite elaborate to build, operate, and maintain, along with the capital expenses involved. Following the progress of innovative work, the force-pump was used for a number of applications, some of which were very important tasks (done by the bronze ones): fire-fighting, bilge-pumping for dewatering a ship, and more casual, luxury tasks, such as spraying fresh perfumed water in the Roman theater and amphitheaters to cool the air. Especially in the Western provinces of the Roman Empire, changing the original bronze apparatus of pumps to a wooden design triggered their common use for lifting water from wells for drinking and gardening. By using wood, some disadvantages were solved; wood, was more commonly available in Western Europe and was less subject to decay under water, in comparison to bronze pumps. Nevertheless, the number of pumps in use may have been quite limited compared to other water-lifting devices that had a higher capacity and were cruder, such as the *noria*, the *Archimedean screw,* and the *shādūf,* for large-scale irrigation. Especially the water-screw has a big advantage, with its robust nature, that allowed its use in coarse-grained and gravel-rich settings, such as draining a mine or using it on a river bank, although no actual remains of the latter have been found. The tread-wheel, with compartmented rim, was also limited to specific areas, in particular, to the mining sites In this respect, the most important issue was to drain high quantities of water from the mines by means of machine power, and to use them for the ore crushing.

From the archaeological remains, it is plausible that the diffusion of water-powered mills started by the 1st century AD, matched with the first serious attempts at industrialization. Generally speaking, the ambitious watermill installations of the Roman world were located close to reliable springs or river sources, far from any dramatic water level changes, and where there was a lot more capital involvement, an expensive aqueduct supply was built. The diffusion of the two main designs of undershot and overshot wheeled mills depended on the features of the different geographical settings, profiting from the power of streams and rivers in relation to changes in local paleo-environmental conditions, or connected to a gravity driven aqueduct. A few examples of the ancient water technologies that have been mapped are still in use today, such as the *Archimedean screw*, *norias,* and gear-driven wheels with a compartmented rim. This means that even after almost three millennia of history, and the accordant technological progress that took place during the time, these mechanisms are still satisfying people's needs in rural areas today.

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