Power and Performance the Water Lifting Machines Used in Ancient Mining in the Southwest of the Iberian Peninsula

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Abstract. One of the main problems that were faced by former miners was the extraction of water in mines. When Romans arrived at the Peninsula, they introduced new technology that gave solution to the problem. However, this technology was not created by them, but this had already used in the development of other activities in the Hellenistic world in the Eastern Mediterranean. Main drainage's systems for indoor works in the mine were: Archimedes' screw, the waterwheels, bucket pulley and Ctesibius' pump. Machines are analysed from their main features and operating way. All of that without forget the most important discoveries in the southwest of the Iberian Peninsula, one of the places that biggest mining use has had throughout history. This work thus provides a qualitative and quantitative comparison of the main mechanisms for mining in ancient Huelva, supposing a basis for directing research in this area.

Keywords: Iberian pyrite belt · Roman times · Water wheel · Ctesibius pump · Archimedes' screw

1 Introduction

The mining activity in the southwest of the Iberian Peninsula, where Huelva is located nowadays, started on the third millennium B.C. with the extraction of copper and precious metals [1, 2]. First mining was approached in superficial way and using primitive technology. It was not until second century B.C., with the arrival of the Romans to the south of the Peninsula, when the mining activity begins to be noticed [3, 4], introducing new techniques to solve the problems that originate the exploitation of this sector at greater depth. One of the main problems that had to face the mining exploitation was the drainage of the water, because of the arrival of new techniques of deepening. The extractive capacity was raised, and in many cases the miners exceeded the water tables. This could even cause the inundation of underground works, with subsequent of exploitation cessation.

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At that time, the different drainage some systems were simple and elementary methods, such us manual extraction through buckets, rope baskets or cubes. Also more elaborated methods were used like the conduction of water through wooden channels and drainage galleries, or the use of machinery to lift them abroad. When the configuration of the terrain prevented the use of the tunnel's systems and galleries, it was necessary to drive the water to a specific point of the mine, or elevate it outside. Lifting mechanisms were used, less stressful and more effective than manual transportation.

The first drainage mechanisms in mining were found in Egypt during the Ptolemaic era. Engineers from Alexandria's School designed some mechanisms made of wood, like a wheel to evacuate water from the inside of the mine. Later, the Romans used the same system in mining works in Britannia (nowadays Great Britain), Dacia (nowadays Romania) and the southwest of Hispania (Riotinto, Tharsis and Sâo Domingos, Spain and Portugal).

The main relevant sources of knowledge in mining tasks are the X books written by Vitrovius, "Architecture of Vitrovius", (Roman architect, I B.C.) along with the work of J. Gonzalo and Tarin (1888) and R. Palmer (1927) in which they noted and graphically described the remains of ancient mining found in Huelva's. However, these devices were expensive and could only be used where the ore was rich [5, 6]. The main drainage machineries documented in Roman times were, Archimedes' screw, Ctesibius' pump and the water wheel [7]. All these water devices were previously used in the Hellenistic period, but the Roman technicians introduced them in mining, also improving their effectiveness. Therefore, the technical contribution of Romans was based on the usage of machines.

The main objective of this article is to review the mechanical systems of water extraction in the SW mines of the Iberian Peninsula in Roman times, an area where there was a lot of mining exploitation. Once the main methods are described, a comparison between the systems is carried out, comparing efficiency, depending on their lifting capacity, flow and energy consumed for its operation.

2 Materials and Methods

Several documentary resources were used to locate the bibliographic documents. Historical Mining Archive of the RioTinto Foundation, in Huelva, provided a massive amount of information, saved by the companies that exploited the Riotinto mines and other mines of Huelva. The Andalusian Historical Heritage Institute (IAPH) was also consulted about the mines.

A recent bibliographic research was made in various databases such us Scopus, Google scholar, Web of Science, Journal citation reports using the descriptors: Water lifting machines, Iberian pyrite belt, Water wheel, Ctesibius pump, Archimedes Screw. A search was also carried out in 'Google scholar' search engine with the same terms. The record obtained were sifted to the Roman times, and ranged between 1850 and 160 records after the combination of different keywords. Documents were selected about relevant information of the water lifting machines used in the SW mines of the Iberian Peninsula in Roman times, its design, construction, applications and lifting capacity.

2.1 Archimedes' Screw

It was invented in the third century B.C. by Archimedes, from which it receives its name, although some similar devices were found in the ancient Egypt. Archimedes based his design on theory, which allows a rational usage [8, 9]. This device is a helical gravimetric machine used to lift water, flour, cereals or excavated material and was based on a hollow cylinder and an endless screw, Fig. 1.

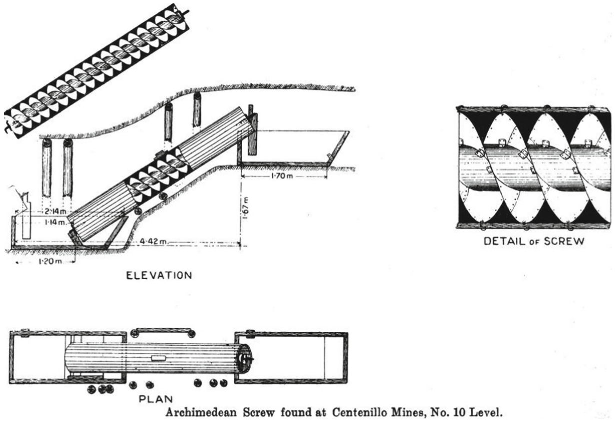


Fig. 1. Description of the composition and operation of the Archimedes' screw [10].

Generally, it was constructed of wood, although in some cases the internal helix was made in metal. Eight parallel lines, equidistant from each other, were drawn along in a trunk. These lines were cut by others, also equidistant, and separated by an eighth of circumference of the axis. At the intersection points of some lines and others were passing some slats, of flexible wood, fixed firmly and glued together with pitch. These wood's strips were those that being fixed in spiral on the trunk, formed the snail or screw. Finally, this piece was covered with wooden slats (convex tables) forming envelope cylinder of the previous piece. The whole set was tarred and solidly held with a rolled rope. It did not raise much, but it could move a large amount of water.

Vitruvius recommended eight partitions for his device, the ends of his axis had to be of iron and once mounted and his casing had to be covered in pitch to avoid leaks. The best inclination according to Vitruvius was based on the Pythagorean Theorem, being about 37°. They were placed in rows, Fig. 2, and they loaded the water from a lower tank to an upper tank, from where it was covered by another screw.

It was activated by human force. A slave worker used a bar placed on top, providing movement, Fig. 3.

From this mechanism, three devices were found in Huelva, all of them associated with a bucket pulley, near the pit of San Juan in Sotiel Coronada's mine (Calañas, Huelva) [13]. Of these three, only one in the Huelva Museum is relatively intact. From the others, pieces are preserved in the Museum of Transport in Glasgow, the British Museum, the Musée des Arts et Métiers in Paris and the Provincial Museum of Huelva. Some copies

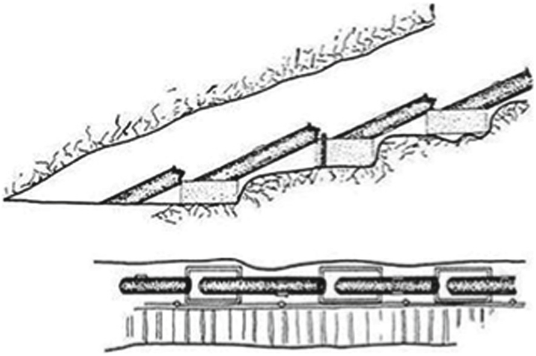


Fig. 2. Archimedes' screw battery [11]

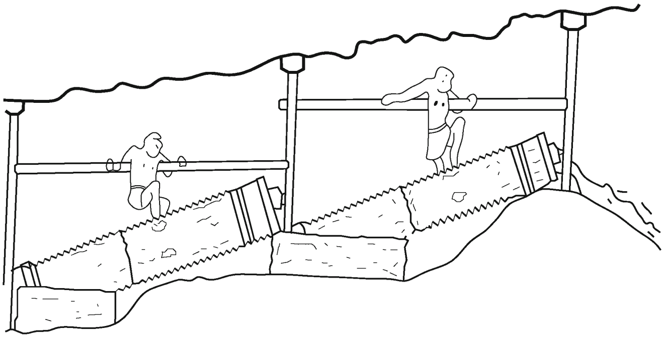


Fig. 3. Operation of the Archimedes' screw [12].

of this mechanism were also located in the Cerro Muriano's mine, in Cordoba Copper Co. And also in Centenillo's mine (Jaen) in Centenillo and Castulo Group, where the best preserved screw can be found. The one that is in the museum has a different size than Vitruvius. This one has a ratio of 1/15, the partitions that form the spiral are three instead of eight and are formed by twenty-five layers of wood sheets in 12 m of height [12]. These plates are fixed with bronze nails greased on the cylinder, and it is covered in pitch together with a rope covered in pitch too, to secure its sealing. Its inclination was 17º.

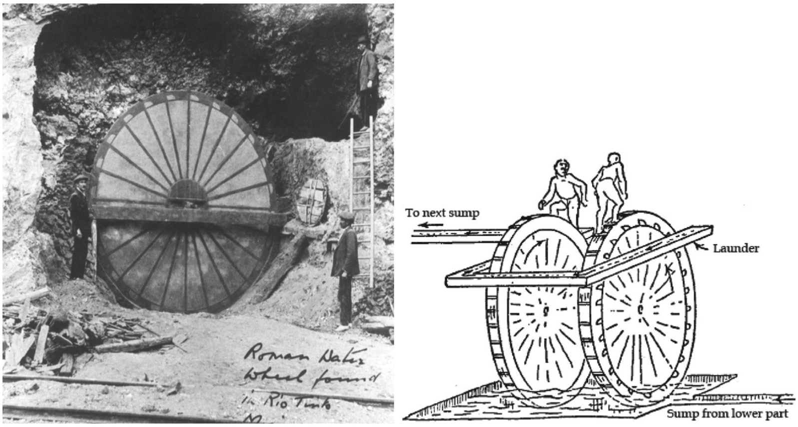
2.2 Water Wheels (Rotate Aquae)

The water wheel is a machine used to raise water, formed by a series of buckets attached to a large wheel. It raises the water from the bottom to the top. A wheel of this type is similar to a carriage wheel, with larger dimensions and with the addition that it has buckets to catch water.

Several civilizations claim the invention of the wheel. There are Indian texts dating from 350 B.C.; Joseph Needham believed that the wheel was developed in India during the fifth or fourth century B.C. [14]. He assumed that it spread to the west by the first century B.C. and then diffused to China by the second century A.D. This was followed by widespread use of the wheel in the Eastern Mediterranean in the 5th century A.D., before reaching North Africa and the Iberian Peninsula in the 11th century. Other possibilities of its origin include the Near East 200 B.C. Philo of Byzantium (ca. 230 B.C.), a Hellenic engineer of the late third or early second century B.C., showed sketches of several distinct types of water wheels.

They were made entirely of wood, but the axis were made of copper (Fig. 4a). The wood was taken from oak in Sâo Domingo (Portugal). The water wheel preserved in Huelva, has three types of wood, walnut for the cube, pine for the buckets and fir for the radios.

The water wheels were preferably placed in pairs, forming batteries. They were placed in different steps. They lifted the water from one step to the next, communicating with each other through short galleries and channels. The couples of water wheels turned in the opposite direction (Fig. 4b), so they put the water in the cannel always with the same direction. Its assembly was made in situ due to its large diameters.



(a) **(b)**

Fig. 4. **(a)** Finding and reconstruction "in situ" of the Roman water wheel found in Riotinto in 1886. (Archivo Histórico Minero Fundación Río Tinto. Minas de Riotinto, Huelva). **(b):** Water wheels with compartments rim; representation based on archeological findings in Spain (adapted from [14])

Some boards were fixed on the running surface, joining the ends of spokes. These tables were used as steps receiving the impulse of the foot of the worker who operated it, sitting at a higher height on the wall in front of the wheel. This was helped by another worker, located in the part of the wheel's axis, which moved the spokes with ropes [12]. Their performance was relatively high, since they could raise large amounts of water to a considerable height (3–4 m).

The water wheels found in the Iberian Pyrite Belt, have been defined as "Hispanic type" and are characterized by being taller, slender and narrow. They have a diameter that varies between 3,60 and 4,65 m. They have a bucket between 20 and 30 cm. Their weight ranges around 200 kg and their number of buckets and spokes are between 22 and 30 [13]. Between 1850 and 1860 ten wheels were found in Sâo Domingo's mine (Mértola, Portugal) the wheel is currently kept in the Musée des Arts et Meters in Paris [15].

About 50% of water wheels discovered in the Iberian Peninsula have been discovered in Huelva. Ten water wheels were discovered in 1875 in Filón Norte's mine. Two fifths of the wheel are preserved in the Museum of Transaport in Glasgow. Later in 1886 at the Lagunazo's mine (Alosno), a pair of wheels similar to those was found in Tharsis [13].

About 50 wheels have been found in Riotinto, but only two are preserved and only one third of them. Also a bronze axis is preserved in the British Museum.

A wooden axis is preserved in the Riotinto Mining Museum too, and eight bronze axis, three wooden discs and a complete wheel found in Masa Planes are showed in the Museum of Huelva (Fig. 5) [16].

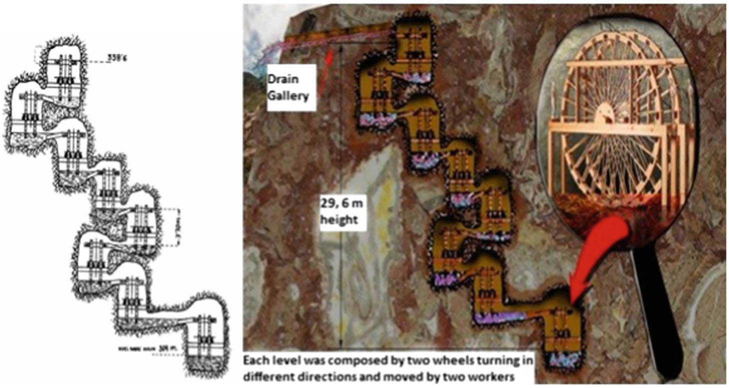


Fig. 5. Roman wheels in Riotinto [16]

Apart from these remains that have been maintained, several pairs of wheels have also been found, as the battery of eight pairs found in Filón Sur or Nerva. These 16 wheels allowed them to move the water 29,6 m from level 309 to 338,9 above sea level.

We need to know the volume of each bucket, the number of buckets, the diameter of the wheel and rotation speed for the calculation of the flow of a water wheel. It is a variant of the previous one, used when the wheel was not effective due to the depth or because the loading area of the wheel had a low level of water, which prevents the buckets to load water correctly. It consists of a hydraulic wheel with a metallic double chain on which were hanging some bronze buckets with a capacity of 3,5 L. Only a few copper buckets found in the Cabeza del Agua (Riotinto) and in Sotiel Coronada's mine (Calañas) are preserved nowadays. This device was found combined with a set of Archimedes' screws.

2.3 Bucket Pulley

The bucket pulley is a variant of the wheel for situations in which the amount of the water extracted was very small, Fig. 6.

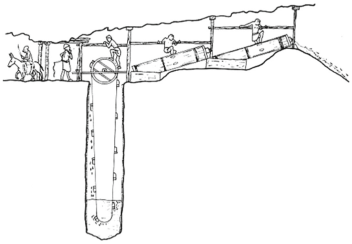


Fig. 6. Draining system combination, Bucket pulleys and Archimedes' screws (Sotiel Coronada's mine, Huelva). [12].

It must be taken into account that the volume of the bucket used to be 3,5 L. In addition, the few machines that are still preserved had 20–25 buckets. Despite the few pieces that are preserved, Sotiel Coronadas' bucket pulley is made in a single piece when it is usually made in two. You can also see two engravings: "Q.CORNELLIV (s)" and "L.VIBI. AMARANTI. P. XII S." [12]. It is believed that these inscriptions were made by the pulleys manufacturers.

2.4 Ctesibius' Pump

According to Vitruvius, his invention is attributed to the Hellenistic Ctesibius of Alexandria in the middle of the third century B.C. This pump consists of two cylinders with pistons that were moved by means of connecting rods attached to opposite ends of a single lever [17]. These pistons converge in a common chamber, in whose entrances there are non-return valves, allowing the water to take a single direction. The central chamber is attached to a nozzle through which the driven water comes out. The nozzle can be oriented in the desired direction and increase the water speed about 25 times, due to the narrowing section. These can be made of copper or lead. To manufacture the perfectly cylindrical pistons they used the procedure of lost wax.

The pump was moved by hand, operating a wooden lever with a swinging motion. Then the water ascends by the piston. The other piston impelled the water contained in the central pipe. Securing in that way a continious flow. By their operation mode, they worked only with clean water.

One of the two pumps of this type that are preserved in Spain, were discovered with a masonry work on the third floor, sleeper 25, Sotiel Coronada's mine in Calañas, Huelva, Spain, [13]. This is the most important device preserved of the Roman world (Fig. 7). It is currently located in the Archaeological National Museum of Madrid.

This pump found in Huelva was made in bronze and its size was 0,95 m high and 0,41 m wide. It had a flexible tube with the form of a T placed at the end of the main tube. Due to their characteristics, it is believed that the main use of this pump was not to


(a) (b)

Fig. 7. Sotiel Coronada's pump, Calañas a) Virtual Archive archaeological national museum and b) Archaeological national museum, (Madrid)

drain water but to pulverize it and cool the pyrite in the demolition system of the hard rock, where the action of the fire was complemented by the water [12].

3 Results and Discussion

Once we have seen the main water extraction machines Roman times mines in the SW of the Iberian Peninsula, we are going to see their performance and capacity and we are going to compare them to each other.

Humans have a limited physical power output, which can be in the range of 0,08 to 0,10 HP. This power can be used to raise water (0,08 to 0,1 HP gives between 60 and 75 watts).

- **Archimedes' Screw**

Talking about size proposed by Landels J. [14] and in the formulation of helical screws mentioned in "Elevators: Principles and innovations" [18] the main operating parameters of Archimedes' screw can be calculated.

The following data are useful: hb = 1.16 m (Lifting height), L = 2.4 m (Screw length), φ = 37° (Inclination angle). With these values and the following expressions we can obtain the water flow that the Archimedes' screw was able to raise.

$$Q = V \cdot S \cdot \rho \cdot 3600 \cdot i \tag{1}$$

$$S = \frac{\pi \cdot D^2}{4} \tag{2}$$

$$V = \frac{P \cdot N}{60} \tag{3}$$

Where:

Q = Flow (l/h); V = Peripheral speed (m/s); S = Area (m^2); ρ = Water density (kg/m^3); i = Inclination parameter; D = Screw diameter (m); P = Step (m); N = Angular speed (rpm).

The usual diameter of similar machines studied is about 0,5 m, the distance between blades can be assumed approximately 0,25 m and the inclination parameter is 0,25 for 40º. This machine was activated by people so we assumed a rotation speed of 10–14 rpm. We are going to use the Eqs. (4), (5) and (6).

The results obtained are these.

$$Q = 0,058\frac{\mathrm{m}}{\mathrm{s}} \cdot 0,19\,\mathrm{m}^2 \cdot 1000\frac{\mathrm{kg}}{\mathrm{m}^3} \cdot 3600 \cdot 0,25 = 9918l/\mathrm{h} \tag{4}$$

$$S = \frac{\pi \cdot 0,5^2}{4} = 0,19\,\mathrm{m}^2 \tag{5}$$

$$V = \frac{0.25\,\mathrm{m} \cdot 14\,\mathrm{rpm}}{60\,\mathrm{s}} = 0,058\,\mathrm{m/s} \tag{6}$$

These results are like Landel's 10.000 l/h. Landels used the same size so we can consider it a valid calculation method [14]. Using these values, the theoretical power can be calculated and compared later with the other devices studied using the following expression:

$$Pt = \rho * \mathrm{g} * \mathrm{Q} * \mathrm{hb} \tag{7}$$

Where:

ρ = Fluid density (kg/m^3); g = Gravity (m/s^2); Q = Flow (m^3/s); hb = Lifting Height (m).

$$Pt = \rho * \mathrm{g} * \mathrm{Q} * \mathrm{hb} = 1000 * 9,81 * 0,0027 * 1,16 = 30,69\,\mathrm{W}$$

For water density of 1000 kg/m^3 and 9,81 m/s^2 The power value is 30.69 W. Finally, we use the expression (8).

$$\mathrm{Pr} = \frac{Pt}{\eta} \tag{8}$$

Where:

Pr = Real power (W); Pt = Theoretical power (W); Ƞ = performance.

This machines were made in wood and knowing that their power came from human people the performance was too low. In this case we assume a performance of 70%, like other writers did [19]. So the real power developed in this conditions and calculated by (8) has a value of 43,84 W.

- **Water Wheels**

According to the biography "Las ruedas de achique romanas de Riotinto" (P. Manzano, et al.) the usual volume of a bucket reached a capacity of 7 l. and the number of buckets, 30 units. The total volume will never be covered so a coefficient of 0,75 is applied. [6] “Note on some Ancient Mine Equipments and Systems”.

$$Volumen_{wheel} = volumen * 0,75 = 5,25l \tag{9}$$

$$Volumen_{wheel} = Volumen_{bucket} * N^{\circ}_{bucket} = 5,25 * 30 = 157,5\,l \tag{10}$$

In a complete round we would have 157,5 L of water. Knowing that the diameter of the wheel was approximately 4,5 m we can assume that the drive speed per person should not be too high. For this study one complete lap per minute has been assumed.

$$Q = \frac{157.5\,\mathrm{L}}{1turn} * \frac{1\,\mathrm{turn}}{\mathrm{min}} = 9450l/h \tag{11}$$

We obtain a value a little higher than the proposed one by Palmer but of the same order of magnitude [6]. The difference is made due to the performance used by the author or to various losses that are not discussed in this article.

Knowing that the lifting height for a wheel is 4,5 m and using the expression (7), You get a power of:

$$Pt = \rho * \mathrm{g} * \mathrm{Q} * \mathrm{hb} = 1000 * 9,81 * 0,0026 * 4,5 = 114,77\,\mathrm{W}$$

In the same way, and with the same performance in the section of Archimedes’ screw (8) the real power of a water wheel is calculated. The value obtained is 163,95 W.

- **Bucket Pulley**

Using the same formulation as in the wheel (9), (10), (11) and assuming a diameter of the wheel of 1 m. driven by a person at a rate of 3–4 turns per minute and with a lifting height similar to 4,5 m and with about 25 buckets:

$$Q = 65,625l * 3\,\mathrm{turn} = 11812,5\frac{\mathrm{l}}{\mathrm{h}}$$

Using (7) the power is:

$$Pt = \rho * g * Q * hb = 1000 * 9,81 * 0,0032 * 4,5 = 141,26\,\mathrm{W}$$

Again using (8) to calculate the power of a pumping machine, with a performance of 70% we obtain 201.8 W.

- **Ctesubius’ Pump**

In this case for the calculation of the real and theorical powers, we begin with the flow data previously established by Martínez Luengo [20] These values are 3320 L/h for the flow and 2 m. of lifting hight (Boletín Arkeolan, 16, 2009–2010).

With these values we obtain the theoretical power from the Eq. (7).

$$Pt = \rho * g * Q * hb = 1000 * 9,81 * 0,00092 * 2 = 18\,\mathrm{W}$$

Applying again with a performance of 70% the real power obtained is 25.71 W.

If the rocker arm operates at 15 cycles per minute, the pump supplies 23 L. per minute and requires an input power of 54 watts. Working with a rocker, a man can probably produce between 40 and 50 watts [19], so it would be difficult for a man to handle this pump. However, two men could do it easily.

However if it is assumed, and they can control the machine, they could drive it faster (for example 20 cycles per minute). The output power will increase to 31 L per minute; and the power requirement increases to 71 watts.

With all this data we are going to try to evaluate which device was the most effective for the water extraction from the mines of the Iberian Peninsula.

Although, there is a question that admits many variants and special circumstances, the best answer we can reach is to compare the options visually.

Below we present a scoring method of flow, lifting height and real power.

A score of 10 is assigned to the best invention in each of the properties that are studied. We will use a rule of three to establish a realistic proportion between the results obtained. In this way, the highest lifting height will have a score of 10 and the rest will be weighted according to the lifting height they raise. In order to compare the three instruments studied, a weighting has been carried out base on the most effective values for each evaluated property. The highest values in lifting height, flow and lower values in power consumed will have a value of 10.

The following table shows the experimental values to be compared in a clear way, Table 1.

Table 1. Devices experimental comparison

	Water wheel	*Archimedes' screw*	*Ctesibius pump*	*Bucket pulley*
Flow (L/h)	9450	9918	3320	11812.5
Lifting Height (m)	4.5	1.16	2	4.5
Power (W)	163.95	43.84	25.71	201.8

Performing the predicted calculations one by one, the following weighted scores have been obtained, Table 2.

Table 2. Devices weighted scores

	Wheel	Screw	Ctesibius	Pulley
Flow	8	7	3	10
Height	10	3	4	10
Power	2	6	10	1
Total	20	16	17	21

4 Conclusions

The results obtained show that the best performing devices are the pulley and the wheel. This is because they move a large amount of water and they have a high lifting height. Their scores are ballasted by their power consumes. However at that time, the people who moved the device were not taken into account, so it should not be an engineering problem. In a second step are clearly the Ctesibius' pump and the Archimedes' screw. The height they are able to overcome makes them ideal for other applications in mining, such as mineral extraction in small galleries, but in terms of pure performance they are behind the wheel and the pulley.

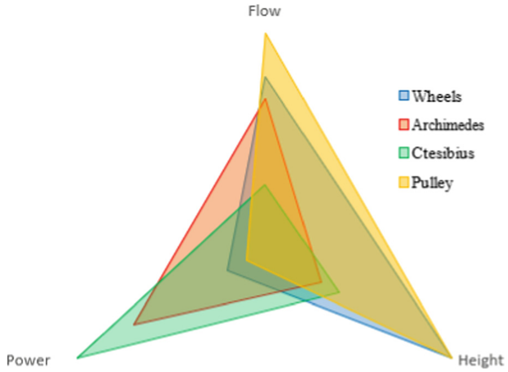


Fig. 8. Results graph

In this graph (Fig. 8) you can clearly see the result. It must be taken into account that the power is considered something negative in this study. The element that consumes the most power has obtained the least score. In this way you can see the result with the blink of an eye (the triangle with more area) and you can select the most efficient devices for water extraction in mines during the Roman era in the Iberian pyrite belt.

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