

ROMAN WATER SUPPLY SYSTEMS

New Approach

Paper presented in
DE AQUAEDUCTU ATQUE AQUA URBIUM LYCIAE PAMPHYLIAE PISIDIAE
The Legacy of Sextus Julius Frontinus
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[Isaac Moreno Gallo](#) © 2015

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Abstract

The main aim of this paper is to synthesize the author's assessments on the Romans' high technical knowledge and skills regarding water supply systems and hydraulic engineering. It will also highlight some key-misunderstandings (still present today in Roman engineering literature) in this particular domain, which are due to the lack of, on one hand, key-archaeological elements and, on the other hand, an appropriate engineering approach to the subject.

One example of lack of archaeological elements concerns water conduits. The supply of drinking water to Roman towns consisted of underground conduits, most of them designed to be operated under pressure using pipes of various materials. Metallic pipes were systematically looted after the fall of the Roman Empire; hence the current lack of information on most of these water supply systems.

An example of the lack of engineering approach is to be found in the current concepts of dams and water reservoirs. The universal source of water supply for human consumption were springs with an abundant and steady flow of good-quality water. Dams were not suitable for the purpose; furthermore, recent research allows us to conclude that they were not used for it.

In addition, most aqueducts had decantation basins. Sometimes they were very numerous and small, and other times remarkably large. However, contrary to common belief, these basins did not store water to regulate water flow, that is, they were not water reservoirs. The same flow that got into them, sometimes very large, went out once decanted. Flow rates that were not consumed were drained to clean the sewage system.

Finally, similar problems can also be found in the topographical domain. The topographical work associated to Roman water supply systems was complex but very accurate, thanks for the instruments used for this purpose. It is important to note in this regard that the current theories on topographical instruments like the *chorobates* or the *dioptra* need to be reconsidered; the proposals made to date are practically useless in the context these systems. More specifically, the interpretation of the table-shaped *chorobates* made by Perrault in the seventeenth century is not tenable, if we make a correct translation of Vitruvius writings.

The following sections will get deeper into the aforementioned issues, looking into the key-elements of water supply in Roman times: The importance of water supply in Roman civilization; water uses and quality; dams and irrigation; methods for water conveyance (non-pressurized and pressurized); decantation; topography.

Meeting water demand

Human water supply was a political and health issue in the Roman World. As it was essential for the maintenance of the Roman way of life, human water supply was guaranteed even before the accomplishment of other public works that were also necessary for the city's development. Not surprisingly, Pliny wrote that "*water creates the city*"¹.

Normally, before building a city, drinking water supply had to be guaranteed. The exact location of the city was often decided by the technical possibility of transporting water into it.

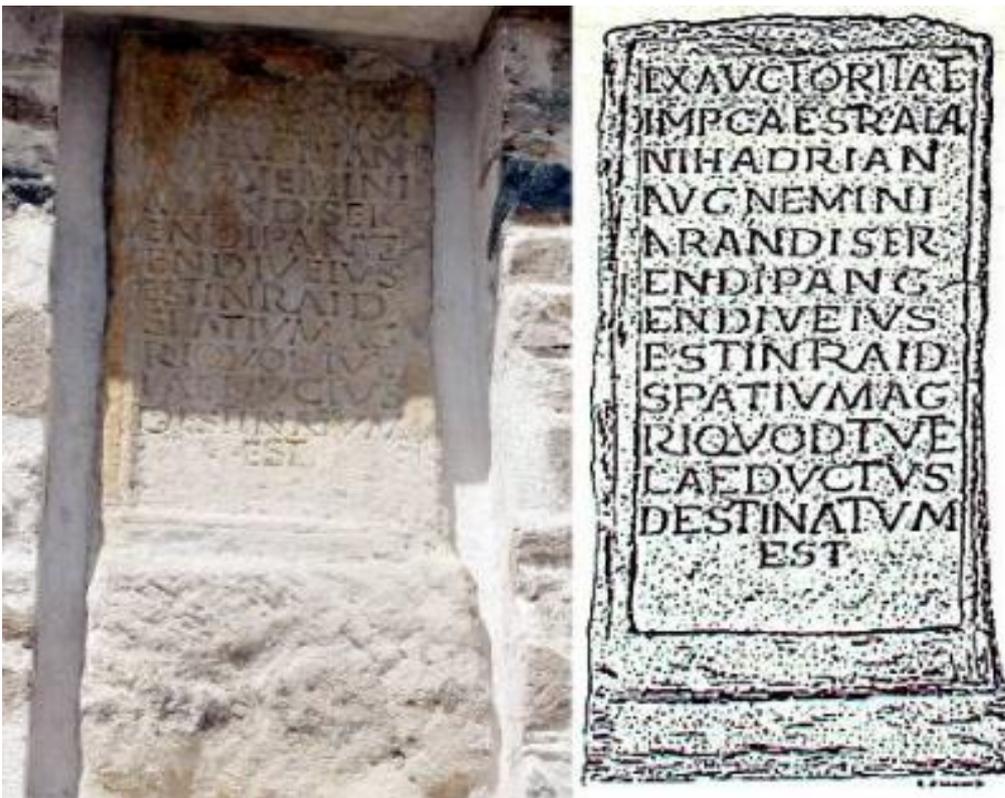
¹ Pliny the Elder. *Natural History*, XXXI, 4.

Vitruvius clearly points to the need to find water in sufficient quantity and quality to ease the city's development and to the way of checking its quality, to convey it and to distribute it².

Water supply was a priority for Roman rulers. Thus, such an essential service was carefully legislated, and administered and provided.

When Frontinus³ took office of *curator aquarum* [water administrator] of Rome in 97 A.D., citing his own words, he did it as an honour granted by the Emperor Trajan. Thanks to his rigour and meticulousness, we know the importance of water administration in Roman cities and many of the legal and technical details enforced, as he recorded them in detail in his works.

Such was the importance of that resource, that channels were legally and physically protected, not only with regards to their proper course, but also as to a wide field on both sides of them, creating a kind of restricted area. To do this, stone markers [*cippi*] were placed near the aqueduct. On the carved text on *cippi* usage limitations were established.



Stone marker (*cippus*) at the Gier aqueduct (Lyon), found in Chagnon: “By order of the Emperor Caesar Trajan Hadrian Augustus, ploughing, sowing or planting is prohibited in this area of land for the protection of the aqueduct”.

² VITRUVIUS. Book VIII. *The ten books on architecture*.

³ FRONTINUS. *De aquaeductu urbis romae*.

In fact, when the Christian started their custom to bury their dead they took advantage of a badly surveyed public land. Thus tombs were dug next to the aqueducts, what caused a serious health problem: *"In relation to the report presented by the Consuls Elius Tuberon and Paulus Fabius Maximus stating that the accesses to the aqueducts that entered the city were invaded by tombs, buildings and tree plantations, the Senate, when being asked for its opinion on the matter, has taken the following decision: ... it has been arranged that in the vicinity of fountains, arcades and walls a space of 15 feet on either side must be left free, and around subterranean channels and galleries within the City and the buildings adjacent to its limits a space of 5 feet on either side ..."*⁴.

Recently, a considerable number of burials have been found next to the Gier aqueduct in Chaponost (Rhône, France), in a place called *les Viollières*.



Burials next to the Gier aqueduct, in Chaponost, at *les Viollières*. A serious health problem after the change of the Roman habit of incineration of the dead. Photo: J. C. Litaudon.

There were people responsible for the surveying, repair and maintenance of channels. Laws clearly established penalties or economic sanctions for breaches or violations of the law, including those concerning water theft or channel destruction that could occur and, in fact, happened, as Frontinus tells us.

In Rome, governed by the rule of law, public interest clearly prevailed over the private one in all domains⁵:

⁴ *Ibidem.* CXXVII

⁵ *Ibidem.* CVI & CVII.

"... The Senate, asked for its opinion on the matter, took the following decision: no private person will be allowed to tap public conduits and all those to whom has been granted the right to divert water, should do it from the distribution basins ..."

"Water rights which have been granted shall not be transmitted either to the heir or to the buyer or to any new estate owner. Long time ago, public baths were granted the privilege to retain their grant of water right in perpetuity. At present all water concessions must be renewed when a new owner arrives".

The zeal to ensure a continuous water supply actually prevented service disruption due to possible contingencies⁶:

"Even in all parts of the city, public fountains, both the new and old ones, received inlets from different aqueducts so that if an accident left one unusable, the service would not be suppressed".

Roman technicians knew how to avoid long interruptions of water supply in case of breakdown⁷:

"No one will question, I think, that the most watched channels should be those which are closer to the city, that is, those that are made up of carved stone from the seventh mile on, because it is not only a work of enormous dimension, but because each aqueduct supports many channels. And if there would be a need to interrupt them, it would leave the city without the largest part of its water supply. There are, however, solutions to address even such difficulties: a scaffold will be built which will rise to the height of the damaged conduit. Then a series of lead pipes are put together to connect the interrupted channel".

Water used for notoriety purposes

Rulers achieved respect and admiration of the [Roman] population by building public works, including those intended for water supply, which were the most appreciated.

The welfare effect that aqueducts had on people was the best advertising that rulers and prominent people could do at that time, and certainly they did not miss the chance to perpetuate their names as benefactors on inscriptions placed with this purpose.



Interpretation of the inscription embedded in metallic letters into the aqueduct of Segovia [Spain], according to A. Ramírez Gallardo, 1975.

⁶ *Ibidem.* LXXXVII. 5.

⁷ *Ibidem.* CXXIV.

We assume that the work's inauguration ceremony would resemble those undertaken presently for our great public works.

The works of water supply to be undertaken between the original source and the distribution point or basin were often technically complicated and expensive. However people did not fully appreciate this achievement because these engineering works were seldom visible to the public.

Perhaps for this reason, on many occasions unnecessary and ostentatious constructions were preferred to the said non-visible engineering works, due to their unquestionable advertising effect. In effect, there are many cases in which large arcades could have been replaced by pipe siphons, which were equally effective and cheaper to build.

When comparing the cost of siphons made of pipeline (*fistulae*) and that of archways (*arcuationes*) money saving was not always taken into account. Should there be a close inhabited area, spectacular arcades with a clear visual impact on population were preferred. They actually guaranteed the promoter's remembrance for generations.

Many of the gigantic and expensive arcades such as those in Segovia, Tarragona (both in Spain) or the large Pont du Gard (Nîmes, France) would not withstand an economic study of construction and maintenance if compared with pipeline solutions. An example would be the case of the aqueduct of Gier in Lyon, in which up to four large siphons, one of them, the Beaunant, measuring 2,660 meters long with a 123 m tall archade. As to these siphons a highly efficient operation could be stated during the life of the aqueduct.



Inlet storage tank of the Soucieu-en-Jarrest siphon, at Gerle, Gier aqueduct. The holes where lead pipes were inserted are clearly visible, as well as the ramp that supported the pipeline.

The serious problems associated to the maintenance of the arcades did not go unnoticed by Frontinus⁸: "*The passage of time or the exposure to bad weather conditions usually affect those parts of the aqueducts which are supported on arcades or those that are attached to the mountainsides and, between the arcades, those parts passing across a river. For this reason, appropriate repairs must be implemented immediately. The subterranean parts, which are not at the mercy of the rigors of the environment (neither frost nor heat), are the least damaged*".

Some particular cases in the Roman Empire deserve specific analysis in this regard: The siphon of Aspendos (Turkey) is actually a succession of three siphons joint by two headertanks. The pipeline, probably made of bronze with stone junctions, remained elevated on a system of arcades keeping a long and stable horizontal course (and pressure) throughout the whole stretch comprised between the towers. Thus a large volume of superstructures could be spared by conveying water under pressure.

Perhaps an economic study concerning a pipeline solution, which would have rested on the ground for most of its length, was more profitable but not enough to discard the "spectacular" option. This can be demonstrated by the resulting visual effect of 1,670 meters of supporting arcades.



Headertank at the alignment variation of the aqueduct of Aspendos (Turkey).

Water usage

⁸ *Ibidem.* CXXI.

As is the case today, a remarkable amount of water in the Roman world was used in agriculture. Dams were built throughout the Empire to store water for irrigation purposes, increasing agricultural production and wealth in a very significant way. Today only a few of these dams are preserved. Sometimes simple derivations of rivers served to irrigate large areas.

Industrial water applications were not uncommon, such as in flour mills, with an example in the mills located at *Berbegal* (Arles), but it was in the mining domain where water brought its most spectacular achievements. Ore washing required large amounts of water supply to specific locations where water supply was not an easy task, bound up with serious engineering difficulties. A well-known case is that of the gold mine in *Las Médulas, el Bierzo* (León - northwestern Spain).

However, the most fundamental water that Roman engineers had to provide was the water for human consumption. Hygiene, health and leisure of Roman citizens depended largely on water.

Cities emerged around springs which had certain healing properties; many were of these were dedicated to water, which was the main reason for their founding. There are many cities in the Iberian Peninsula that include the word *water* in their names: *Aquae Celenae* (Caldas de Rey - Pontevedra), *Aquae Quintiae* (Baños de Guntín - Lugo), *Aquae Flaviae* (Chaves), *Aquae Querquennae* (Baños de Bande - Orense), *Aquae Oreginis* (Baños de Río Caldo - Orense), *Aquae Bilbilitanorum* (Alhama de Aragón - Zaragoza), *Aquae Voconiae* (Caldes de Malavella - Girona), *Aquae Calidae* (Caldes de Montbui - Barcelona) y *Vico Aquario* (north of the Duero river, in Zamora).



Aquae Querquennae (Baños de Bande - Orense). City originated from a camp founded in a place with several springs with abundant flow of hot water (40° C), by the *Via Nova*, between *Astvrica Augusta* and *Bracara Augusta*.

All Roman cities had water, although it is true that in most cases the specific system of water supply used in those times is not known. It is understood that, when the population increased, new supplies from other sources were needed and added.

Only a few supply systems used arcades in channeling. Therefore, only a few are still visible as vestiges. Most channels were subterranean, being either a covered trench or a pipeline. This might be a reason why there is so little information available on them. There are also difficulties in the identification of the sources and Roman water catchments due to the fact that the origin of water for supply is not known at all.

Supply of drinking water

It is necessary to insist on the crucial issue of drinking water quality, which was the primary target sought by Romans when thinking of water supply. The best reference in this regard are the writings of those who lived at that time.

In the texts of *Frontinus* we can see how important the quality and the taste of the water were in Rome, representing an issue that came to be considered a matter of state. Similarly, we find in these texts many of the techniques used to achieve the best qualities at the catchment areas and to allocate water of less quality for other uses.

According to Frontinus⁹:

I: "...I have been commissioned to manage water supply, an appointment that concerns not only the city's water provision but also its health..."

LXXXIX: "And what about the fact that the industrious spirit of the emperor, punctually available to serve his citizens, has thought that so far little has been done when providing abundant water, considering that he might not contribute appropriately to our safety and enjoyment if he does not transform it in something more pure and pleasant?"

So, it is worth to examine through what means he has corrected the defects of some conduits, increasing the utility of all of them. Indeed, when did our city, after rain, scarce or abundant, have neither murky nor muddy waters? This does not happen because conduits have that natural original defect nor because the problem originates in the springs, from mainly the Marcia and Claudia, whose transparent waters, intact from their springs, do not get clouded or just a bit, provided that conduits are covered."

XC: "The two conduits of the Anio River are less clear, as they take their waters from a river (from a stream) and often get muddy even in good weather, for the Anio, though it comes from a very clean lake (upwelling) due to its water speed it erodes the banks and gets muddy before it reaches the channels. It is a disadvantage to which we are exposed not only during the winter and summer rains, but even in spring, the season during which we doubtlessly need better water purity" (because of the higher ambient temperature).

⁹ FRONTINUS. *De aquaeductu...* ob. cit.



Great spring of Neissoun. Catchment area of the aqueduct of *Forum Julii* (Frèjus - France) during high water period in spring.

XCI: *"The New Anio was contaminating the others, because as it arrived at a very high level, and especially bringing a great volume flow rate, it compensated for their shortfalls of water supply. Incompetent plumbers diverted its flow to other aqueducts more often than necessary, even polluting aqueducts provided with sufficient flow and especially the Claudia, which had its independent channel along many miles, and once in Rome it was mixed with the Anion, thus losing its quality."*

"We have found that even the Marcia itself, very nice for its freshness and clarity, was supplying its water to baths, fulling mills and even to places unworthy of being mentioned."

XCII: *"Thus, the separation of all aqueducts was ordered, and the distribution reordered, so that the Marcia could entirely be used for drinking water supply, and each other set aside for appropriate uses, depending on the quality needed. For example, the Old Anio that for many reasons and precisely because being caught at a lower level is less healthy, should be used for watering gardens and for the more deleterious services of the same City."*

XCIII: *"The Emperor was not satisfied after having restored the volume and quality of the other aqueducts, and he foresaw the possibility of eliminating the deficiencies of the New Anio. So, he gave the order to abandon the uptake of water from the river, and search for a new source, in the lake situated above the Villa of Nero, in Subiaco, where the water is clearer."*

"Thus, having now the Anio its source (catchment) at the top of Treba Augusta, either because it descends through rocky mountains with few cultivated land around the fortress, or because it releases its sediments in the ponds in which it is decanted, and being also covered by the shadow of the surrounding forests, it arrives very cold and clean."

"Thanks for these peculiar water conditions it can match the Marcia quality in all its properties and even surpass it with respect to the flow rate, replacing the previous dirty and murky water, while an inscription mentions the Emperor Caesar Nerva Traianus Augustus as its recent builder" (again in search of the advertising effect and the perpetuation of the Emperor in the people's memory through the Public Works).



People at all levels enjoyed water. The modest homes had at least a bath as this bronze one at Herculaneum (Italy).

We have therefore seen how Romans sought the most suitable drinking water, meaning thereby the water that originally was the clearest, the coldest, collected at higher altitudes, and better-tasting.

Once this water was collected, they insisted to maintain its qualities at all costs, covering the channels and avoiding sunlight, preventing solids entrainment by lowering the water speed, and eliminating contact with erodible material.

Specific thesis have confirmed the imperial aspirations described by *Frontinus*. It is important to note in this regard that some of these thesis, particularly the technical - constructive study concluding that dams in Mérida (Spain) are not of Roman origin, lead to a wider problem by questioning the use of water kept in reservoirs, stagnant or of poor quality for human consumption in the Roman world¹⁰.

Other classic texts support the said concerns of Roman technicians to preserve the population's health:

Vitruvius, Book VIII¹¹:

1: "*The waters that run through flat terrain are brackish, thick, somewhat warm and unpalatable ... except those that come from the mountains, which, following an underground course, sprout*

¹⁰ FEIJOO MARTÍNEZ, S. 2005: *Las presas y los acueductos de Agua Potable, una asociación incompatible en la Antigüedad: El abastecimiento en Augusta Emerita*. Published in *Augusta Emerita. Territorios, Espacios, Imágenes y Gentes en Lusitania Romana*. Nogales Barrasate, T. 2005 (Ed. scientific). Mérida (Spain).

¹¹ VITRUVIO. *The ten books...* ob. cit.

amidst the plain. In the shade of the trees they are as nice as the waters of the springs in the high mountain.

If there are springs that make the water flow out, it will be easy to dispose of it; otherwise, springs should be searched and caught under the ground."

3: *"For all this, we should take the utmost care and skill in finding and selecting good springs to protect the health of humans."*

6: *"The masonry work must be vaulted, in order to protect the water from sunlight."*

Palladium, I¹²:

4: *"Water healthiness is recognized as follows: first, it must not come either from pools or ponds ..."*

17: *"It is hygienic to make (rain) water run through brick pipes and collect it in covered basins; for springwater is the best of all to drink, to the point that while one can resort to river water, this should be left to the baths and the cultivation of orchards due to its lack of healthiness."*

Therefore, we have to consider the conclusion that drinking water in the Roman world was sought mainly in quality springs, in galleries or catchments made for the purpose, or in cold and quality mountain waters, caught from small lakes or mountain streams. Wells would only cover water supplies where the previous mentioned catchments were not available.

Reservoirs holding stagnant water did not use to have sufficient quality for the intended healthy function, and if they would meet the requirements, their quality was neither permanent nor verifiable by Roman technology, which in these cases was based on empirical methods.

Given the possibility of catching water out of springs and having the appropriate technique to bring water from far away, sometimes covering remarkable distances, the fact of relying on reservoir water (however good it might be) for drinking uses involved a high degree of risk and was actually far from the Roman good sense and pragmatism.

¹² PALADIO: *Tratado de Agricultura*. Biblioteca Clásica Gredos, nº 135. Traducing Ana Moure Casas (1990).



One of the manholes of the catchment galleries of the Rabo de Buey aqueduct in Mérida (Spain). A powerful aquifer was intercepted by a system of horizontal galleries which were then channeled towards Avgvsta Emerita. Today water still continues to run through the conduit.

We know of several cases of distant catchment areas, more than 100 km away from the population that had to be supplied; distances between 50 and 80 km between the source and the town were actually very common. That occurred even in regions where water was not scarce, for example in Gaul: The aqueducts of Nîmes and Arles are over 50 km long and two of the aqueducts located at Lyon are 70 and 86 km long, respectively. In Germany, the one in Cologne is 95 km long.

There are many cases where catchment areas have been misidentified, associating them to sources that the Romans would have never used, thereby fostering theories that pointed to the use of rivers or reservoirs for drinking water. Such is the case of the current Zaragoza (*Caesaraugusta*), where for years it had been assumed that the Gállego river would have been diverted, just 20 km from the capital, to supply water to the Roman population¹³. However, even at a lesser distance one can find the powerful springs that supplied the city, existing documentary proof regarding their use by the Romans¹⁴. Due to its pressure, quality, height and distance, it served not only to supply the Roman city, but decisively determined the place of its foundation. It can be said today that Zaragoza owes its location to those springs.

¹³ GONZÁLEZ TASCÓN, I. 1994: *El Acueducto Romano de Caesaraugusta*. CEHOPU. MOPTyMA.

¹⁴ Basically from the mathematician Josef Costa of the 17th century, in a report where he suggests to restart the usage of the Roman water collection system to supply Zaragoza. Published by: BLÁZQUEZ HERRERO, C. 2005, p. 20 y ss.: *Zaragoza. Dos milenios de agua*.



Powerful spring in La Joyosa (Zaragoza), today underused despite its water volume, belonging to a large group of springs from which water was carried to Caesaravgvsta

Dams and irrigation

The role of dams in the Roman world is not sufficiently clear today. Since recent research seems to show that water storage was not intended for human consumption, these structures could only be used for agriculture, for the irrigation of large areas.

Large agricultural subdivisions in the Roman world occupied flat and perfectly irrigable lands, many of which still fulfill that mission.

The traces of the great Roman plots (*Centuriatio*) known in Spain, especially in the Ebro valley, as the ones in *Caesaraugusta* (Zaragoza)¹⁵, *Cascantum* (Cascante), *Graccurris* (Alfaro) and *Calagurris* (Calahorra)¹⁶, occupied the same land portion that is irrigated with modern channels today.

Throughout these areas there are small-sized dams of undetermined age and old pools already filled with sediments, intended for water storage. A more romantic than scientific vision has aimed to bring many of these structures back to the Roman world; however, they are the remains of more recent works undertaken through history in order to continue their mission of supplying water to these areas.

Large areas of irrigable land of *Narbo Martius* (Narbonne), *Arausio* (Orange), *Arelates* (Arles), and *Nemausus* (Nîmes) next to the Rhône river (France) have their origin in the Roman world. In these cases, as well as in the aforementioned cases from Spain, simple derivations of the Rhône and the Ebro rivers or their tributaries would be enough to provide irrigation areas (ditches system) with sufficient water.

Irrigation meant a dramatic increase in agricultural wealth and the ability to produce high

¹⁵ ARIÑO GIL, E. 1990: *Catastros Romanos en el Convento Jurídico Caesaravgvstano*. La Región Aragonesa.

¹⁶ ARIÑO GIL, E. 1986: *Centuriaciones romanas en el Valle Medio del Ebro*. Provincia de La Rioja.

value alimentary products in large quantities (the horticultural varieties of that time). The market generated by this new production system generated enormous wealth areas where previously only a reduced indigenous population survived.

In other cases, large Roman dams are known in that area, but the irrigation field or traces of the plots are unknown.

In Spain, authentic Roman dams are rare (much rarer than those assumed as such)¹⁷. This is also true with regards to other structures of this period.

We understand as clearly Roman those constructions with a masonry work that is aligned with the construction procedures of the time.

Regarding the case of the dam of Almonacid de la Cuba (Zaragoza) with a storage capacity of six million cubic meters and a closing wall thirty feet high, it is estimated that it would irrigate more than seven thousand acres¹⁸. It was probably one of the highest dams in the Roman world, although most of its masonry work cannot be considered Roman, being the result of subsequent additions.



Dam of *Almonacid de la Cuba* (Zaragoza), built at a place where the river Aguasvivas gets narrower.

¹⁷ The related literature, as it happens with other structures, dates almost all ancient dams as from the Roman time, although there is no document that could assign their origin to a determined time. To summarize, you can see the large number of supposedly Roman dams, although the one of Muel has been omitted, included in the work:

DÍEZ-CASCÓN SAGRADO, J Y BUENO HERNÁNDEZ, F. 2003: *Las presas y embalses en España. Historia de una necesidad. I. Hasta 1900*. Ministerio de Medio Ambiente.

¹⁸ HERESA, J. I., ARENILLAS, M., DÍAZ-GUERRA, C., CORTÉS, R., BELTRÁN, M., VILADÉS, J. M., SESMA, A., UTRILLA, J., LALIENA, C. 1996: *La Presa de Almonacid de la Cuba*.

For most researchers, the dam of Muel (Zaragoza) has long been the most probable source of water supply for *Caesaraugusta*¹⁹. A gallery dug twenty feet above the elevation of the reservoir of the dam has even been described as a bypass channel for these purposes²⁰, though it was actually intended for an electric wiring in the 20th century, which bears no relation to the Roman dam or the Roman world.

Most likely, this reservoir was limited to irrigation of a wide area of the Huerva river meadows, serving agricultural production in the cities of *Contrebia Belaisca* (Botorrita) and *Caesaraugusta* herself.

As a result of the passage of two millennia, the bed of all these dams' reservoirs is now silted up.

Known dams: Typology and construction

Among the truly Roman dams known in Spain, we can only mention, due to the accuracy of their dating, the one of *Almonacid de la Cuba* (Zaragoza) and the one of Muel (Zaragoza).

The Roman origin of the dams of Proserpina and Cornalvo in Mérida has been questioned recently²¹, with well-founded criteria. Many other dams located in Spain and today considered Roman, but in fact they do not meet the required structural features and there is not sufficient data available to consider them as such. In other cases, reforms or subsequent additions hide or complicate the identification of their Roman parts. That is the case of the dam located in the Roman city of Andelos (Navarra), now promoted as a reservoir that supplied drinking water to the Roman city²² in spite of not corresponding at all with the characteristics of a Roman masonry work.

It is necessary to clearly state that the number of dams currently considered as Roman, mainly in Spain, is enormous. But in fact, there is hardly any proof that could confirm this. In addition, none of them matches Roman building models.

The authors who stubbornly advocate the idea of Roman dams being used for drinking water supply²³ actually feed in the aforementioned ideas: "The most updated studies we know on

¹⁹ ARENILLAS PARRA, M. Y CASTILLO, J. C. 2003: *Dams from the Roman Era in Spain. Analysis of design Forms*. First International Congress on Construction History. Madrid, 20th-24th January 2003.

²⁰ ARENILLAS PARRA, M. 2002: *Obras Hidráulicas Romanas en Hispania*. Paper presented and published in the framework of the 1st Congress on Roman Public Works, Mérida, Spain (2002).

²¹ FEIJOO MARTÍNEZ, S. 2005: *Las presas y los acueductos de Agua Potable, una asociación incompatible en la Antigüedad...* ob. cit.

²² MEZQUÍRIZ IRUJO, M. A. 2004, pp. 287-318: *De hidráulica romana: el abastecimiento de agua a la ciudad romana de Andelos*. Published in: *Trabajos de arqueología Navarra*, N° 17.

²³ ARANDA GUTIÉRREZ, F. 2006: *Las Presas de Abastecimiento en el marco de la Ingeniería Hidráulica Romana. Los casos de Proserpina y Cornalbo*.

the subject indicate the existence of 73 dams or catchment areas of Roman origin in Spanish territory"²⁴

In the light of above, it has to be noted that that many other ancient dams in the Mediterranean area which are considered of roman origin will require a detailed study in the near future to clearly determine their allocation (or not) to the group of Roman structures.

Dams which are clearly Roman

Concerning the dam of *Almonacid de la Cuba*, a comprehensive study was conveyed, both from the technical-constructive and from archaeological point of view²⁵. The results, very interesting in many aspects, revealed the existence of a previous dam before the one which can be seen today, which was embedded inside.

Both seem to be of very different types. The first dam is a multiple arched dam, consisting of (probably) three arches and buttresses. As it has been said above, this dam is today embedded in the one that is currently visible. The current spillway was part of the first dam, more specifically of one of its arches. The water intake is a common element to both.

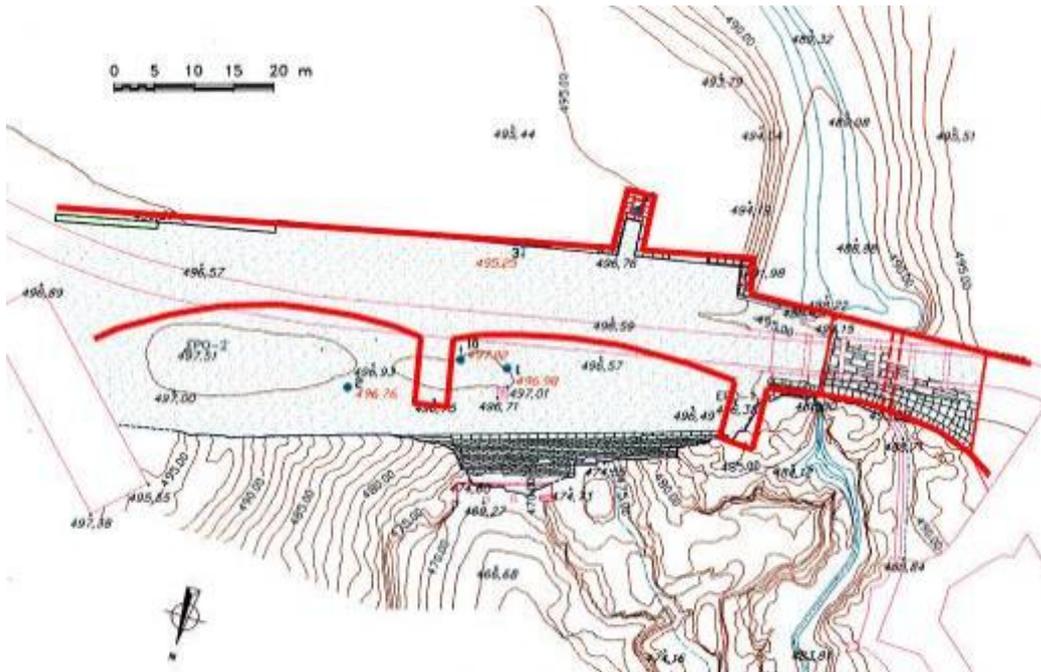
However, a review of its construction technique reveals a clearly Roman masonry work in the spillway and the upstream faces that were once excavated. All these elements are assignable to the first dam. In those masonry works we can systematically observe ashlar, well-squared and attached one to another without mortar, stapled with double dovetail-shaped staples, and other fully Roman features²⁶.

The last dam, which covers the first, has a trapezoidal section, with stepped gables on both faces, reinforcing the final structure. No Roman elements are observed in this dam, which has the largest volume of masonry work and from a subsequent time. They are often formed of lime concrete which is impossible to date, has ashlar which are squared in a way that is not attributable to the Roman world, bound with mortar, with no bossage, no staple imprint nor any other element that can define it constructively as Roman.

²⁴ CASTILLO BARRANCO, J. C., ARENILLAS PARRA, M. 2002: *Las presas romanas en España. Propuesta de inventario*. I Congreso de Historia de las Presas. Libro de actas. Diputación de Badajoz.

²⁵ HEREZA, J. I., ARENILLAS, M., DÍAZ-GUERRA, C., CORTÉS, R., BELTRÁN, M., VILADÉS, J. M., SESMA, A., UTRILLA, J., LALIENA, C. 1996: *La Presa de Almonacid de la Cuba...* ob. cit.

²⁶ Regarding these issues, it is indispensable to consult specific references on roman masonry: DURÁN FUENTES, M. 2005: *La Construcción de Puentes Romanos en Hispania*.





Part of the masonry of the spillway at the wall at the downstream face. It is a vestige of the older dam that is still visible, with a clear Roman masonry. The bossage and the way ashlar are fit correspond to a Roman construction. The vault of the arch has been rebuilt.



Upstream face wall. Here we can see obvious Roman walls, which covered the dam's core made of concrete. Some ashlar have been taken out at the upper part. In the foreground, there is part of the spillway that has been reconstructed with common ashlar (with no bossage). Photo: J. M. Viladés.

We have several news on reconstructions of this dam. One is repeatedly documented in time

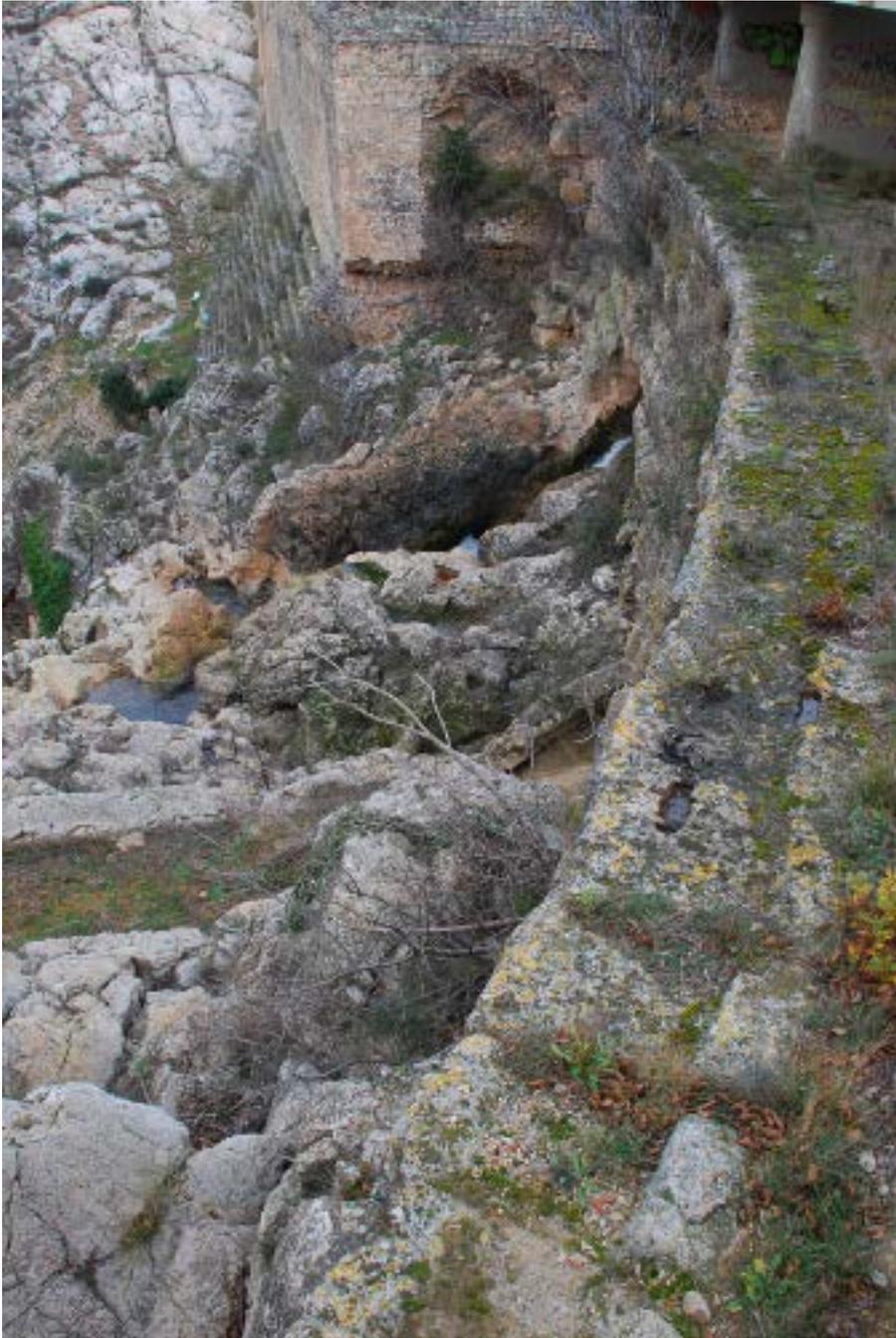
of James I the Conqueror, but probably the stonework that can be observed today even belongs to later times.

The Muel dam has a unique structure. Its outer body coating shows a large, well adjusted, ashlar ensemble, perfectly joined together.

We can observe perfectly cubic ashlars of 2x2x2 feet along with other prism-shaped ashlars of 2x2x4 feet. Joints made of alternatively assembled headers and stretchers are closed and tight on the outer layer of ashlars.

Inside, in the core of the dam, a lime and stone concrete seals the open vertical joints (up to half a foot). Nevertheless, the horizontal joints are assembled without mortar.

A recent cleaning of the upper part and both faces of the dam has revealed some marks of unknown meaning.



The *Almonacid* dam where the Roman arch is perfectly visible.



General view of the downstream wall of the dam of Muel. The upper part keeps ashlars assembled without mortar with closed vertical joints. The lower part has lost its outer coating.



Detail of ashlars at the inner level of the dam's coating, at the downstream face. Vertical joints are open, half a foot wide, being filled with concrete from the core of the dam.



Top view of the body of the Muel dam, wherein we can see the core of ashlars held together with lime concrete, and the upstream outer coating with closed joints bound without mortar.

Much remains to be explored with respect to the identification of dams of the Roman world. This is due to the absence of evidence of the Roman origin of almost all dams identified as such in the Mediterranean. We cannot certify the Roman origin of almost none of the various types of dams that have been built throughout history: Gravity dams made of masonry work, of concrete or of a combination of both; dams made of loose materials; arch dams, etc. While the masonry work of the dam in Muel has a core made of concrete, that in Almonacid reveals multiple arches, as the arch that is visible in the spillway, although the dam probably worked by gravity.

We also have news of the existence of an arch dam in Glanum (Saint- Rémy de Provence, France) which was replaced by another in the 19th century. Traces in the rock, where the ashlar were embedded, seem to confirm that²⁷. There is little evidence for accurate dating. Some other dams were thought to be Roman as they had arches, like the one of Esparragalejo (Badajoz). However, in this particular case the poor work leads us not to consider it as such. There have probably been more domed masonry dams. These withstand very well the pressure and are perfectly suited structures for water containment. Today, we can only certify a small number of them throughout the Roman world, which does not mean that there could not have been others²⁸.

²⁷ AGUSTA-BOULAROT, S., and PAILLET, J.L. 1997: *Le Barrage et l'Aqueduc Occidental de Glanum: le Premier Barrage-Voûte de l'Histoire des Techniques* (The Dam and Western Aqueduct of Glanum: the First Arch-Dam in the History of Techniques) *Revue Archéologique*, No. 1, pp. 27-78 (in French).

²⁸ CHANSON, H. and JAMES, P. 2002: *Une histoire révisée des barrages-voûtes. Des barrages romains aux ouvrages modernes en béton*. Australian Civil Engineering Transactions, Institution of Engineers, Australia, 2002, Vol. CE43, pp. 39-56.

Large dams which cannot be attributed to a particular period or without a Roman typology.

The Syrian dam of Harbaqa is a large and impressive work, with a length of 365 m and a height of 8 m.

In this dam the outer coating of ashlar has partly disappeared, especially in the lower half, what also happens in the dam of Muel. In Harbaqa the concrete layers from the core are exposed, while in Muel what can be seen are the ashlar from the core. In the Harbaqa Dam, however, no clear characteristic structural elements of Roman masonry work can be distinguished, despite the spectacular nature of the work. Later civilizations could have perfectly been the architects of this dam.



Overview of the Harbaqa dam (Syria). Photo: M. Duran.

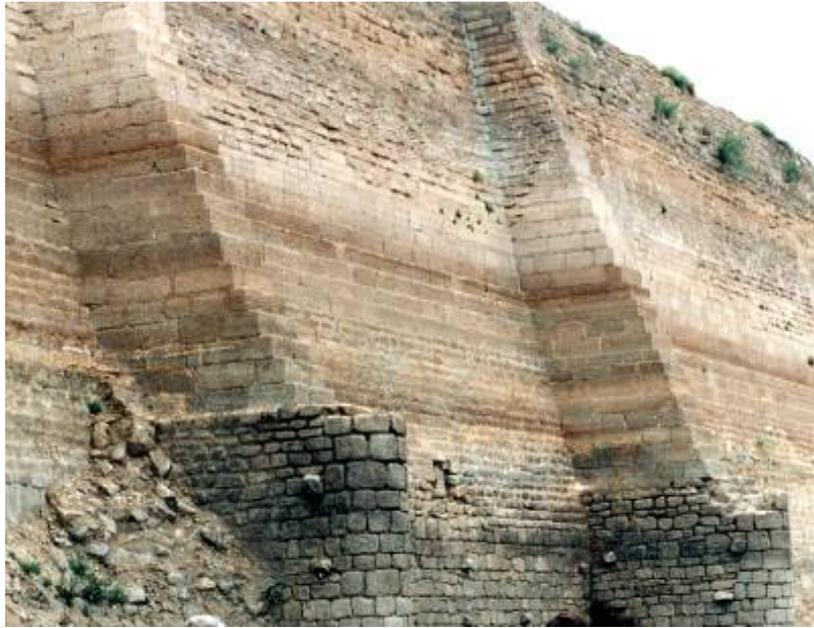
In Spain, dams around Merida have been considered Roman for a long time by the majority of authors who have studied them. Nevertheless, they show masonry work that is improper for that civilization.

Recent well-founded studies²⁹ show that the lower part of the Proserpina Dam in Mérida is clearly medieval, so the rest will necessarily be more modern. This dam did neither supply water to the aqueduct of Los Milagros (the Miracles), nor drinking water to Emerita Augusta by any other means.

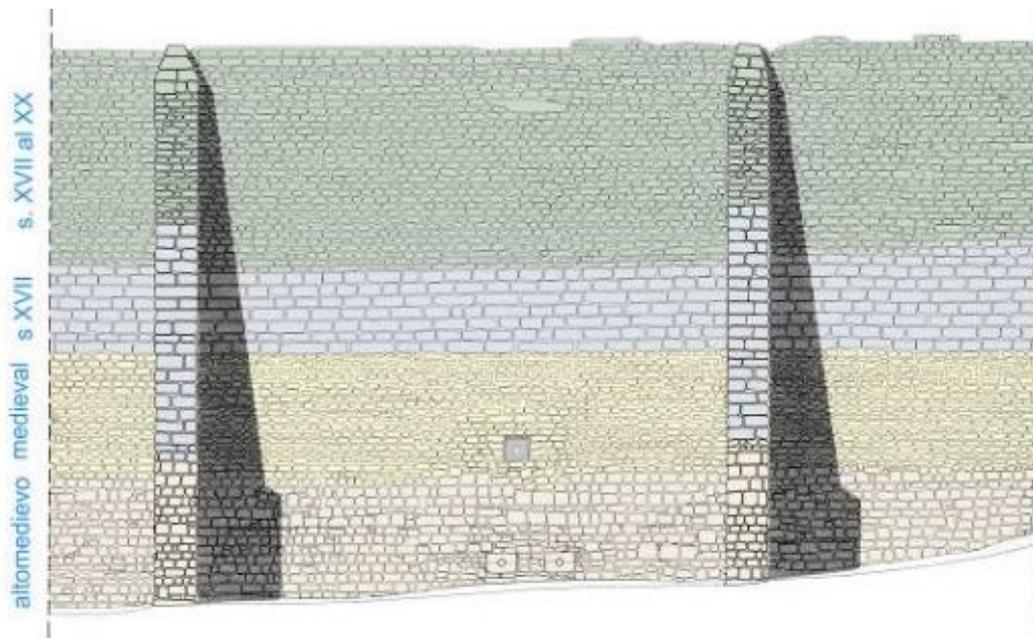
²⁹ FEIJOO MARTÍNEZ, S. 2006, pp. 145-166: *Las presas y el agua potable en época romana: dudas y certezas*. Nuevos elementos de Ingeniería Romana. III Congress of Roman Public Works. Astorga.

Its enormous dimensions of 426 m long and 21.6 m high make it truly spectacular. Although it has bossages (a characteristic of Roman stonework), it must be said that these have also been reproduced extensively in the centuries of the Enlightenment.

Moreover, the construction of dams in the Islamic world is well-proven in the Middle East and, for sure, such works were performed during the presence of that civilization in Spain. Many of the dams in southern Spain and of course those next to Merida, a very important and populous city in the Middle Ages, might have their origin at the time.



Upstream face of the Proserpina dam. We can distinguish very different types of masonry work. Those at the lower part are worse and less “Roman”. Photo: Thomas Porro.



A chronological interpretation based on the typology of the different masonry works of the Proserpina Dam, made by FEIJOO (2006), has been based on the plan from the photogrammetric study by the “Confederación Hidrográfica del Guadiana” [Guadiana River Basin Authority]

The Cornalvo dam, presumed as Roman for a long time, finally seems to be entirely modern and was not used to supply drinking water to the Roman city³⁰. The intake tower has traditionally been identified as a Roman stonework, but its particular isolation from the rest of the dam and its dubious role as an intake tower lead to the conclusion that these elements should be set apart from the dam.

The connection channels made in the ground to convey water to the dams show masonry of very poor quality, which is improper, even more so, of a Roman construction.

The Alcantarilla Dam in Mazarambroz (Toledo) has been regarded as "undoubtedly" Roman by all authors who have considered it. Several studies include it in the water supply system to *Toletum*³¹.

Again, its large size, about six hundred feet long and twenty of maximum height, make it spectacular. It has been designed with a trapezoid base, a central waterproofing barrier and an earth wall.

However, its masonry is very heterogeneous: Some of it is very irregular and even of bad quality, in combination with lime concrete which is impossible to date. Other parts of the masonry are series of well-aligned and even ashlar covering the concrete layers. The presence of gravel has been confirmed, which is infrequent and improper concerning Roman stonework.

The relation with a hypothetical conduit to the Roman Toledo is not proven at all. It is a non-documented engineering work of remarkably large dimensions and a high construction cost. But none of this makes it Roman. It is important to note in this regard that the channel deriving from it is called "Juanelo" by locals. This is an interesting hint leading to a probable Renaissance origin, more specifically to the authorship of Juanelo Turriano.

³⁰ *Ídem*

³¹ ARANDA, F., CARBOLES, J., ISABEL, J. L. 1997: *El sistema hidráulico romano de abastecimiento a Toledo*. Instituto Provincial de Investigaciones y Estudios Toledanos.
ARENILLAS PARRA, M. y BARAHONA OVIEDO, M. 2008. *Una revisión general del suministro de agua a Toledo en época romana*. IV Congress of Roman Public Works. CITOP. Lugo.



Facing with regular ashlars, well-arranged, but filled with tiny cobbles, forming the shuttering of the coating of lime concrete in the Alcantarilla dam. It is not a Roman masonry work. Besides, it shows a clear contrast with the irregularity of the ashlars of other parts of the dam. Photo: C. Blázquez.



Alcantarilla dam: View of the poorer facing areas (from a constructive point of view). Photo: C. Blázquez.



Details of the alleged intake tower of the Alcantarilla Dam. The poor masonry work and ashlar assemblage correspond to medieval or modern times. Photo: C. Blázquez.

There are other dams along the *Aguasvivas* river (Teruel) which are smaller than that of Almonacid and have also been considered Roman³².

Such is the case of the dam located in the municipality of Muniesa (Teruel), called the “Wall of the Moors”, with 68 m long and 8.5 m high. The large size of this lime concrete wall covered with stonework recall the old splendour of historic engineering. However, its masonry differs radically from Roman construction typology.

In the same river basin, equally impressive for its size is the dam of the Chapel of the *Virgen del Pilar*, 80 m long and 16.7 m high. It is sunken and broken by the apparent mediocrity of its construction technique; in brief, an improper engineering work.

The absence of documentation on these works helps, and too much, to regard them as of Roman origin. But most likely they are just the remains of medieval or later works aimed at the improvement of agricultural production in the irrigated river basin of the *Aguasvivas* river. Therefore, these represent an inheritance of those times and not from the old Roman Empire.

³² HEREZA, J. I., ARENILLAS, M., DÍAZ-GUERRA, C., CORTÉS, R., BELTRÁN, M., VILADÉS, J. M., SESMA, A., UTRILLA, J., LALIENA, C. 1996: *La Presa de Almonacid de la Cuba...* ob. cit.



View of the poor, badly squared and badly levelled masonry work of the dam called the Pared de los Moros (the Wall of the Moors), in Muniesa (Teruel). Photo: C. Blázquez.

Poorly engineered dams

Amongst the large number of dams that are supposed to be Romans in Spain, we can mention some that are precisely the least likely to have a Roman origin. Their construction technique is unbecoming of a competent technician, or at least, it may be said that their conception lacks engineering science, which makes them even less Roman.

The lack of documentation supporting the construction time of an ancient engineering work causes recurrent speculation, thus leading to the assignment of the authorship to any given civilization, with no solid basis.

However, there are tools that are used for the analysis of ancient constructions and for their allocation (or not) to the Roman world. Nowadays the analysis of the various preserved engineering works of the Roman civilization compels us to consider the participation of real construction scientists. No public works conceived and designed by employees of the Roman State, engineers ultimately, should lack the basic elements of advanced Roman building techniques.

Therefore, in the presence of works of poor construction technique, with non-geometrical ashlar, unnecessarily irregular, badly attached parts, structures that look creaky, poorly consolidated, badly levelled, etc. it is necessary to conclude that the incompetence of its constructors has no place amongst Roman engineers.

There are always works for which a structural analysis leaves a reasonable doubt on their dating. However, some of the dams that are proposed as Roman by some authors do not hold up when confronted with an analysis in the sense indicated above.

One of these works is that on the dam of Consuegra (Toledo). It is in most of its length nothing but a simple lined wall, whose function as water retaining wall should be questioned after a thorough structural analysis. It has buttresses only in its central part, although its height does not change too much along the entire wall.

Its lateral parts have a rectangular section, as wide above as below, and relatively slender. A badly designed gravity dam, without a doubt.

Its work is of lime concrete made with large irregular stones, which are poorly consolidated. In brief, this dam fits perfectly in the category of dams with ugly appearance, poor masonry and an obviously improvable design.

To conclude, this dam must have failed shortly after being put into service as its reservoir has no accumulation of sediments, what does demonstrate the poor design of the work from its very beginning.



Overview on the poor concrete wall that sets up the dam of Consuegra at both ends. Stretch without buttresses.



The Consuegra Dam, made of a large mass of concrete, with little lime. Stretch with buttresses

In the vicinity of Mérida, there is knowledge of dams of a certain entity but of remarkably poor and irregular masonry. The cases of Esparragalejo and Araya are the most significant. Esparragalejo was rebuilt in 1959 and thus it is partly covering the original work. Photographs taken before its reconstruction show a large work of poor execution. Its wall with buttresses with arched faces between them reaches 320 meters long and 3.6 meters of maximum height.

Such structures, consisting of timeless lime concrete and construction technique, impossible to date, with poor execution, are clearly unbecoming any Roman work.

It is also important to highlight the frequent attribution of stoneworks to the *opus incertum* construction technique as a pretext for considering them Roman. However, this does not actually reduce the uncertainty on its Roman origin.

Araya is a dam near Esparragalejo, with a similar typology, but smaller. It has a buttressed wall about two feet thick, with a concrete central shelter wall just two feet thick, and in this case, with no arched face. It has not been reconstructed, and thus confirms the statement about her elder sister.

With respect to the hydraulic system of the city of Andelos in Mendigorria (Navarra) it is necessary to distinguish several masonry works which are clearly different and belong to other constructive times.

Although the existing literature dates the whole group as Roman, due to its simple proximity to the Roman city, its construction technique appears to indicate the contrary.

Some elements of Roman works have been subsequently utilized, as it happened with the water storage basin located next to Andelos. However, most of the work that we can now see and is taken for Roman is unlike any Roman ashlar assembling construction technique, and of poor quality too. The walls intended to be in contact with water have inwardly buttresses and seem to be a reinforcement to those made of lime concrete.

In this basin near Andelos we can clearly see the Roman waterproof mortar coating (*opus signinum*), which is in contact with a good concrete wall, probably from a Roman reservoir that was later covered. On the layers of concrete, we can observe a good quality aggregate which was brought from far away and is not included in the surrounding poor masonry works. Besides, the amount of lime contained in the layers and its hardness are excellent. The rest of the work which completes the basin, expanded to twice its original area, bears no relation to these techniques and corresponds to a very bad ashlar stonework, typical of medieval and later periods.

Regarding the dam located about three kilometers from Andelos, we can see two different construction techniques: A poorly built wall of ashlar (of identical stonework as the one of the basin described above) reinforcing another wall at the upstream face, which is very different and has large buttresses of lime concrete. Between both walls, the presence of a layer of impervious soil (perhaps clay) can be inferred; it must have disappeared with the archaeological excavation carried out some time ago³³.

Unlike the Roman concrete covered with a waterproof coating of mortar, described with respect to the basin of Andelos, this concrete work has a different construction technique. Here, the layers have poor and uniform contents of lime, and aggregates are much worse, more heterogeneous, different from the ones in the basin, and probably originated from its

³³ MEZQUÍRIZ IRUJO, M. A. 2004, pp. 287-318: *De hidráulica romana: el abastecimiento de agua a la ciudad romana de Andelos...* ob. cit.

surroundings. Even in the unlikely event of it being Roman, based on what has been previously said, that dam did not serve to supply drinking water to the Roman city.



Roman basin made of concrete next to the city of *Andelos*, coated with *opus signinum*, in the foreground. It was widened to build a reservoir with a wall of buttresses of poor work, made in more recent times.



Detail of the *opus signinum* coating the concrete layers, made of high quality thin and homogeneous aggregate. It belongs to an ancient deposit and are part of the basin next to *Andelos*.



Concrete wall with large buttresses at the dam located three kilometers west of *Andelos*. In the upstream face a second wall made of irregularly arranged ashlar was built, which is separated by a small section of soil from the first.



Double wall dam located three kilometers west of *Andelos*. One of the walls is made of concrete with thick cobbles, very different from that of the basin close to *Andelos*. The second

dam, at the upstream face, is made of irregularly arranged ashlar, is separated by an earthfill section from the first dam and has buttresses.

There are many other smaller dams which have a poor masonry work and are equally impossible to date on its own evidence, but they were assigned to a specific time in history due to the fact that some archaeological remains were close to them.

Such is the case of Santa María de Melque in Puebla de Montalbán (Toledo), which has been assigned to the Visigoth period for the aforementioned reasons³⁴. Here we will find a group of small concrete dams, made of aggregates of irregular sizes and very poor lime contents. Had the Visigoth remains not been close to them, it would have been probably attributed to the Roman world, as it happens so often³⁵.

Finally, we can find other cases which are almost surreal, like the small retaining wall of los Bañales (Uncastillo -Zaragoza), appallingly poor, which has been regarded as Roman by its simple proximity to the Roman site. This low wall of awful stonework, which cannot be very old, is made of irregular blocks, absurdly smaller at lower levels, resting on the ground in rows without any leveling. This type of structure could not function as a dam in any way. No minimally competent engineer would have undertaken such nonsense with the objective of retaining water, however archaeologists that have studied it have wished it to be so³⁶.



³⁴ CABALLERO ZOREDA, L. y FERNÁNDEZ MIER, M. 1999, pp. 199- 239: *Notas sobre el complejo productivo de Melque (Toledo). Prospección del territorio y análisis del Carbono 14, polínicos carpológicos y antracológicos y de morteros*. Spanish Archaeology Archive, n. 72.

³⁵ As he already thought they were: FERNÁNDEZ ORDOÑEZ, J. A. 1984: *Catálogo de noventa presas u azudes españoles anteriores a 1900*. CEHOPU.

³⁶ ANDREU PINTADO, J., ARMENDÁRIZ MARTIJA, J. 2011. *La presa romana de Cubalmena (Biota, Zaragoza) y el abastecimiento de agua a la ciudad de Los Bañales*. Published in *Cæsaraugusta*, 82. 2011, pp.: 199-221. ISSN: 0007-9502.

Retaining wall that is taken for a Roman dam in Los Bañales (Uncastillo -Zaragoza), despite being built of irregularly assembled ashlar, which are smaller at lower levels, resting on the ground in rows without any levelling.

Transporting water

The Art of levelling and successfully transporting water until its destination without experiencing any losses represents one of the most difficult and beautiful disciplines of civil engineering.

Roman engineers admirably solved the combined problem of conveying water across slightly inclined channels through terrains with a difficult topography, avoiding water loss during the water's journey, overcoming obstacles that nature put in the course of the channeling system, and ensuring a long-lasting work, due to the features of its own design.

All these factors had to be taken into account when designing a water conduit. The result had to be conclusive to be able to choose non-pressurized water channels, where water is driven by its own weight, under free-flow conditions, due to the force of gravity. Or, if it is not possible, a forced solution should be chosen. That is, where water flows under pressure, in a closed pipe, and is pushed and forced by adjacent water masses, being able to rise up thanks to the force of the water masses located on the opposite site of the conduit.

All these aspects were mastered with ease by Roman's engineering science, to the point of being used as a reference and school for modern engineering science.

Besides, Roman drinking water channels had to go underground or be totally covered throughout their entire length. This was useful to maintain water freshness and quality. Even in the upper parts, such as over walls or arcades, the channel was always covered.

This can be checked nowadays by watching known channels, and so did *Vitruvius* deliberately state (VIII, 6)³⁷: *The masonry structure of the channels must be arched over, in order to protect water from sunlight.*

³⁷ VITRUVIUS. *The ten books on Architecture.*



Part of the channel, still vaulted, which is preserved over the arcades of the aqueduct of Forum Jvlii. Frèjus (France).

Non-pressurized water

Today's civil engineers know the trade-off between the water speed in the channels and the work's durability, being aware that a difficult balance has to be maintained.

Even in channels made of concrete or metal, which have the most resistant walls, water speed should be limited, since the work's wear caused by the fluid itself can become unacceptable. Obviously, in channels with weaker coatings such as those made of clay, water speed should be minimal. Even channels coated with ashlar will have to take care of this highly destructive factor.

The water speed in the channels is directly dependent on the channel's slope. The steeper the slope, the faster water flows. The roughness of the wetted surface also determines the speed, but to a much lesser extent.

In the modern world, there are also channels and ditches that are easily ruined, due to design defects associated to inadequate slope, or other factors that cause turbulent water flow. Repairs, which are always expensive, require to cover channels with more resistant and durable materials.

One can be surprised when reading the Natural History by *Plinius*³⁸ who indicates that: *channels must be as solid as possible, and their slope should not be less than a quarter inch per hundred feet of length.*

This extremely small slope equals to a 20 cm drop per km, which results in 0.02%. Despite this, this slope is the most common in known Roman channels. In fact, a channel as that of Nîmes (France), which is 52 km long, scarcely exceeds that percentage and keeps lower slopes during much of its course.

Although it is not difficult to find slope tables of many of the known Roman aqueducts, usually they will not come from precise topographical work.

Non-pressurized Roman water channels were often carved into the rock, but, when digging into the earth, the ground was paved with boxes made of blocks of stone (*opus vitatum*) or concrete (*opus caementicium*), in which case an additional coating of waterproof mortar was applied. This mortar was composed of lime, sand, and crushed ceramic (*opus signinum*).

This layer of mortar, which was in contact with water, sometimes had a special thickness, depending on the leakage risk, or rather, the risk that leaks would mean to the aqueduct structure itself. Thus, on the boxes of some of the aqueduct arcades a thickness of up to half a foot, 15 cm of *opus signinum*, was found.



Thick waterproof mortar coating (*opus signinum*) in the box located over the arcades of the aqueduct of Barbegal in Arles (France)

Finally, for any type of channel (channels built in masonry, channels cut in the rock) the features of their interior walls and the water itself were considered, seeking for a balance between slope and speed to avoid channel erosion or extra sediment deposition.

³⁸ Pline l'Ancien. Histoire Naturelle. XXXI. (VI). 1. Traduction française: É. Littré.

Then as now, mistakes were made in this regard. Just a few of these mistakes have been attributed to the roman period and, as it has been confirmed, they led to very high costs.

Sometimes the entire aqueduct died due to the excess of lime depositions, reducing water flow in such a way to make it no longer usable. The impossibility to carry out an appropriate maintenance was the main cause. On some occasions, it was necessary to install a parallel conduit in specific sections, either to retrieve the needed flow or to achieve the flow when a miscalculation as to the required slope happened, (causing that the required speed in that specific stretch was not achieved).



Arcades from the aqueduct of *Forum Julii* (Frèjus) that Romans were forced to double in the stretch of Escoffier. Probably due to a slope problem the aqueduct was not able to absorb all the water flow produced.

Being the water flow the result of multiplying water speed by the channel section, in both cases the aqueduct's problem became evident either causing upstream overflowing or creating pressure in the vaulted conduit at the deficient section, causing in both cases considerable damage to the channel.

However, despite what has been believed to date, the formation of calcareous concretion in aqueducts did not necessarily mean its write-off. The constant maintenance of the aqueduct was a reality, in times when the Roman administration was in effect. In relation to some of the aqueducts in Rome, it is known that they were subjected to the removal of calcareous concretions in order to bring their section to its original shape.

The same thing did not happen as to the aqueduct of Nîmes (France) or to that in Cologne (Germany). Probably due to times of crisis during the late Empire, when a proper state administration did no longer exist, or competent technicians couldn't be found, the lack of maintenance works meant that no action was undertaken for the removal of calcareous concretion or any other measures which would have prevented the death of the aqueduct.



Calcareous concretion (sinter) which chokes off the channel of the Roman aqueduct of Cologne (Germany).



Calcareous concretion that was chipped in order to restore proper flow in the section of the aqueduct of Anio Novus, near Castell Madama, Lazio, Italy.

The arcades, almost always located at the final sections of the Roman conduits, were the most difficult to maintain. Their weakness, compared to that of the underground constructions, was apparent, and *Frontinus* himself testifies this in his texts.

However, some arcades in Rome itself, stood the test of supporting two overlapped conduits, and even three in some cases. This overweight, added to the original design of the arcades, forced to strengthen them, over enormous lengths, creating new internal structures added to the original arcades, which multiplied the bearing capacity of the final structure.



Arcades reinforced with an inner brick structure, in the aqueduct of Aqua Claudia, over which the Anio Novus passed later on.



The Porta Maggiore in Rome. Passing point of the Anio Novus over the Aqua Claudia when entering the city.

Manholes (wells) were uniformly distributed along the conduit to ease its maintenance. Besides, in the galleries excavated into the rock, these wells also served to facilitate the simultaneous excavation on several fronts and the withdrawal of materials. They also served to ventilate the conduit, to facilitate the setting out works through the introduction of the main alignments (by means of plumb bobs and ropes) and finally to mark the aqueduct's alignment on the surface, thus controlling the aqueduct's right of way.



Manhole, 35 m high, in one of the subterranean galleries of the aqueduct of *Vxama Argaela* (Soria).

The geometric control that the Roman engineer had over these underground channels was almost total. Even today, the setting out of the narrow galleries of several kilometers in length would be difficult. But, in the Roman world, we know of the existence of several of them having an impressive length. The channel from Albarracín to Cella (Teruel, Spain), has a five-kilometer-long tunnel. It has wells of up to 60 m deep³⁹, over its whole length. This length is comparable to the one of the gallery that served to drain the lake Fucino (Italy), which reaches 5.64 km and was made in the time of Claudius, though this one was built with wells as deep as 122 m⁴⁰. There are longer tunnel lengths in the Empire. We know, for example, that of the aqueduct of Aix-en-Provence (France) which is about seven kilometers

³⁹ MORENO GALLO, I. 2010. *Análisis técnico y constructivo del acueducto romano de Albarracín a Cella. Las técnicas y las construcciones de la Ingeniería Romana*. V Congress of the Obras Públicas Romanas. Córdoba, 2010.

⁴⁰ DURAND-CLAYE, A. 1978: *Mémoire sur le dessèchement du Lac Fucino*. Paris, Dunod. Annales des Ponts et Chaussées, XV.

long and has wells up to 80 m deep⁴¹. The aqueduct of Drover-Bergh-Tunnel (Germany) has a channel of only 1.66 km, but it is suspected that the Bologna aqueduct (Italy) has an uninterrupted tunnel of about 20 km⁴². Finally, Professor Matthias Döring of Hydromechanics, University of Darmstadt, discovered a few years ago that the aqueduct of Gadara (Jordan) had a 106 km tunnel. Almost all of the aqueduct is an uninterrupted gallery.

At present, many of these channels are unknown, but we know that feats of this type were also achieved in the world of mining, where water conveyance requirements for mining purposes or for drainage reached impressive parameters.

For example, we can mention the case of *Coto Fortuna*, a location belonging to the mining area of Cartagena-Mazarrón (Murcia, Spain), where water circulated through a 1.8 km long gallery, which had a section of 1.30 x 2 m and was situated 70 meters below the surface⁴³.

To get on with accuracy at this underground level is of much greater technical difficulty, especially as to the topographic setting out, than that needed for the construction of many of the attractive arcades that supported the aerial conduits. It is also true that some of the great arcades, which still remain, are stunning architectural works. As noted, several of these works have an excessive aspect for the role assigned. Indeed, they played a propagandistic role, as they generated a clear impact on population, as it still happens. This could not be achieved with the large underground galleries, technical achievements that again today remain unknown or undervalued.



⁴¹ LEVEAU, P. 2006, pp. 93-108: Les aqueducs d'Aquae Sextiae et la gestion de l'eau sur le territoire de la cité. Extrait de MOCCI Florence et NIN Nuria, Aix en Provence. Pays d'Aix-Val de Durance (13-4). Paris. Maison des Sciences de l'Homme.

⁴² GIORGETTI, D. 1985, pp. 37-107: *L'acquedotto romano di Bologna: l'antico cunicolo et i sistema di avanzamento in cavo cieco*. Acquedotto 2000. Bologna. L'acqua del duemila ha duemila anni.

⁴³ GUILLÉN RIQUELME, M. C. 1997: *Mazarrón 1900*. Ayuntamiento de Mazarrón.

Channel carved in the rock following a contour line near the surface and then covered, probably with wood planks. Roman city of Termes (Soria).

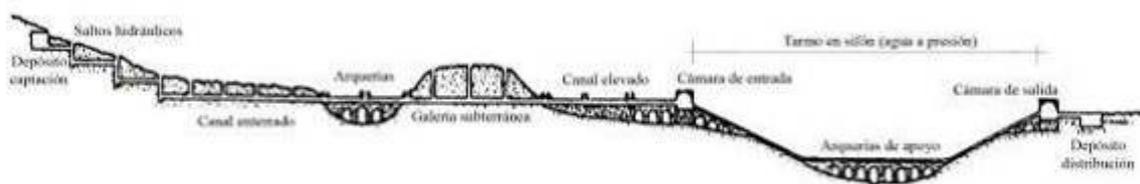


Final part of the excavation in rocky ground and beginning of the vaulted coating of the gallery crossing loose ground. Gallery of the Gier aqueduct, at the so called Cave du Curé, in Chagnon (France).

However, most of the length of the channels was just below the land surface. The most common technique was to dig the channel, following the appropriate contour line, then covering it. Once the gables were built, it was necessary to provide a cover system such as vaults, slabs, etc., and finally with the terrain soil.

When the water flow that had to be conveyed was low, and the required section was accordingly smaller, then a pipe made of stone or ceramic could be installed underground. That pipe could convey the non-pressurized water, or low-pressure water in better conditions, ensuring tightness.

In any case, the tightness of large conduits was always assured using waterproof mortars in the joints of the different parts that make up the channel (when made of carved stone) or, as mentioned above, by coating the entire wetted channel surface (when made of masonry).



Linear outline of a Roman aqueduct showing the different constructive solutions that were common in such works. Drawing of P. Leveau with our own nomenclature.



Waterproof construction joint of opus signinum in one of the cisterns of Lugdunum. Lyon (France).

Pressurized water

Covered channels made of masonry and galleries cut in the rock were common for the supply of large water flows to urban areas. However, when flow rates were low, or the situation afforded the implementation of pressurized water, pipes were installed. These could be mainly of ceramic, lead or stone.

Sometimes, the whole conduit was composed of pressurized pipes. At other times, this solution was implemented on a single section.

Almost always it was more advantageous to resolve valley crossings by means of using pressurized pipes. Only if a spectacular-propagandistic effect was sought engineers turned to arcades which raised the channel.

But in other cases the use of pipes was not advisable: when both the pressure applied in the pipes and the water speed were very low and this happened over a long length of the conduit.

These cases could cause operational problems, due to obstructions or the formation of carbonates in the interior⁴⁴.

In these cases the construction of arcades to convey non-pressurized water were preferable. Although these arcades were longer, they would be smaller, easy to access and to maintain.



Image of the large siphon of Patara (Turkey), made of stone pipe.

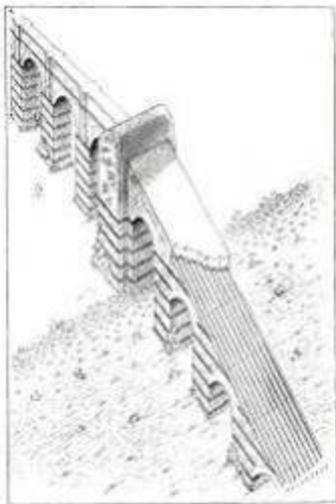
⁴⁴ *Pipes made of lead or ceramic are used (Vitruvius, VIII, 7, 1), but lead pipes, when in touch with water, produce white lead (Vitruvius, VIII, 7, 9). White lead is a basic lead carbonate. It is solid, of white colour, and is used for paintings.*



Ceramic conduits of different diameters, in Efesus (Turkey).

Siphons were installed using a single pipeline or a series of them. Romans had specific masonry to ensure that pipes were properly fastened to the ground, if this was required to withstand the pressure that was put on them (water height). These technical elements, contrary to what is commonly believed, were very common in the supply of cities, and in some cases of impressive sizes.

Roman engineers mastered pressurized water conduits perfectly, as it is demonstrated in many achievements we know today. From the analysis of the situation of the towns of that time, it follows clearly that very few were lucky enough to have a water supply system consisting of non-pressurized water exclusively. Normally they needed to implement siphoning, at least in particular occasions.



Enormous ramp consisting of nine descending pipes belonging to one of the siphons of the Gier aqueduct in Chaponost.



Roman lead pipe, where the technique for the construction of linear and transversal joints can be perfectly seen. Museum of Ancient Arles.

The section of Roman pipes, like that of the channels, was measured in *quinaria*, *senaria*, *denaria*, etc. as *Frontinus* reports thoroughly in his treaty on Roman aqueducts. These measures were referred to the diameter of the conduit, that is, its section.

Actually, the water flow rate carried by the conduits, including pipes, was also measured in *quinariae*, since Romans only considered the section of the conduit in the required flow distribution.

Hereby, they did not consider the speed factor in the calculation of flows. As water was conveyed within a small range of slopes and speeds, they based the calculation of flow rates on section measurement. Under these circumstances, the water volume carried per unit of time, the flow rate, is constantly proportional to the conduit section. Therefore, the flow can be inferred from the section. Thus, in the Roman world the flow is measured in *quinariae*, which is a section measurement⁴⁵.

Only in a few cases Roman lead pipes have been preserved to this day. Those that remained on the surface were looted after the fall of the Roman Empire, due to the value of the metal. Of the thousands of tons of lead pipe belonging to the four giant siphons of the Gier aqueduct supplying *Lugdunum* (now Lyon, France) no trace has been found. Just the name of the

⁴⁵ DE LA PEÑA OLIVAS, J. M. 2008 (not published study): Interesting and reasoned deduction, with which I fully agree, extracted from the detailed study of the treaty that *Frontinus* dedicates to the Aqueducts of Rome.

hillside where one of the siphons was located, that of Genilac, now called "La Plombière" reminds us of this ancient construction.

Decantation

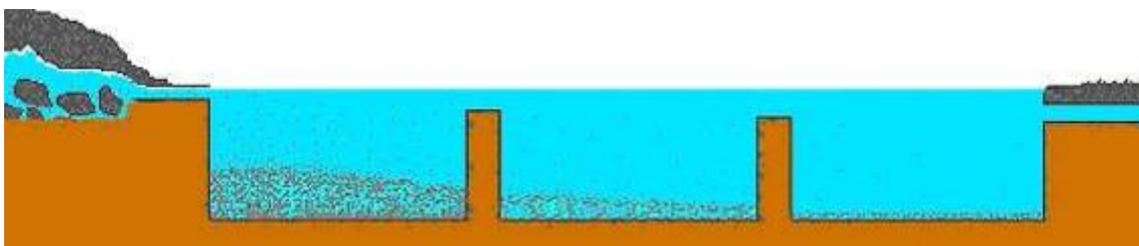
The quality of water used by Romans was generally excellent, from the catchment area onwards. This condition was pursued thoroughly and almost always achieved. Romans had no chance of purifying water from the bacteriological or chemical point of view, and by no means, they could risk to supply polluted water.

Therefore, the method used was the search for the best quality and the prevention of the conduit's deterioration, and it was not a bad method at all. However, mineral impurities in suspension were frequent. They often came from the spring itself, but, above all, they were generated during the course of water through the channel, whose wear produced many of this impurities.

To avoid a high water speed that would cause erosion in the channel, the channel slope was carefully studied and calculated according to the nature of the wetted surface area. Regardless of the height difference between the catchment area and the destination, this was the main factor which determined the slope.

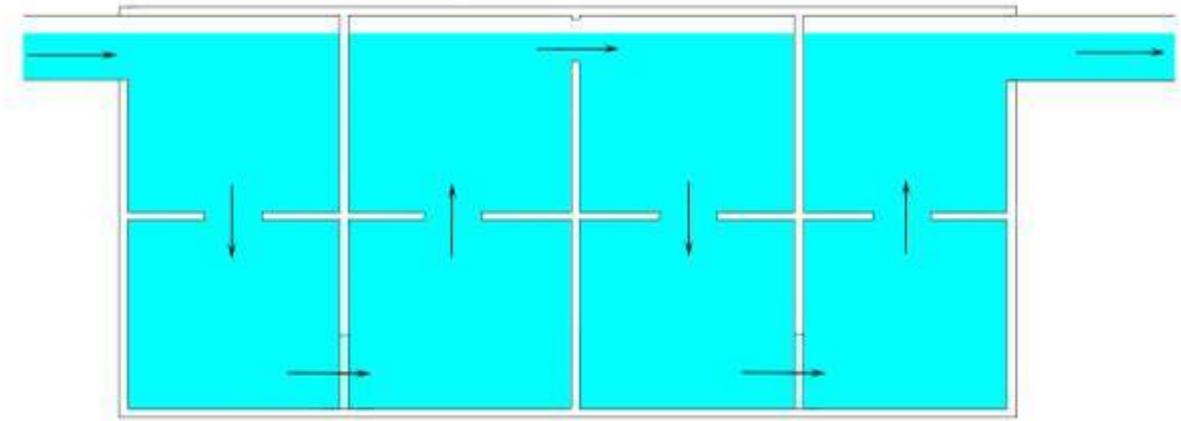
However, the rock on which the galleries were carved, the waterproof coatings, the soil that got into the channel along the aqueduct, etc. caused impurities. Therefore, special chambers where build to force a sharp water speed reduction, by means of suddenly widening the channel's section. Thus, suspended particles settled at the bottom, decanting.

Sometimes it was considered necessary to set these settling basins at the exit of the spring, thus obtaining a useful first sand removal. Other times these basins were established at the point of arrival to the town, and many other times the distribution basins themselves were used for this purpose.



Scheme of the decantation process at the catchment area, next to the spring, composed of several settling chambers.

These basins, with a plant divided in several compartments and even consisted of more than one level of storage chambers, were able to dramatically reduce the water flow rate, forcing it to follow a much longer course and thus to decant all of the suspended solids that it might carry.



Functional diagram of a large settling tank formed by multiple cameras on two levels, making the water move very slowly.

At a constant flow rate, when a channel arrives at a large tank a remarkable section increase takes place, which reduces speed in the same proportion. In addition, if water is forced to flow at a very slow speed for a long time, the removal of suspended solids will be total. Water would then become crystal clear, no matter how muddy it was when reaching the tank.

If these systems were not sufficient, intermediate settling basins were set on the course, by means of artefacts generally used for other functions, such as manholes or drinking fountains.



Sand settling basin in a manhole of in the aqueduct of Carthage (Tunisia). Photo: J. C. Litaudon.



Sandbox in a manhole in the aqueduct of Tiermes (Soria).

These manholes were good-sized and their bottom was lowered thus creating what we now call sand settling basins. They were cleaned regularly and played an important role as intermediate decanting basins⁴⁶.

At the end of the conduit were the greatest settling basins. These deposits could be either a single very large one, or several smaller interconnected basins, or a set of both types.

Sometimes the deposit itself was a great feat of engineering, due to its immense size. The case of Carthage (Tunisia) was famous, where the immense decanter consisted of fifteen elongated parallel chambers, each 7.4 x 102 m long. A true giant with a volume of 60,000 m³. In these cases, while some chambers were cleaned of sludge at the bottom, others remained full, developing their decanting function.

Many others of enormous size are known throughout the Empire, but the topography of towns sometimes forced to seek less spectacular, but not less effective, solutions.

Contrary to the popular belief, it seems now demonstrated that in the Roman world water was not stored. These remarkably large deposits did not have a water storage function (for water flow regulation); their mission was simply to decant and to purify water from its suspended solids. Each litter of water arriving into these decanters, always at the top of the chambers, went out at the other end, again from the top. Sometimes it took several days to complete the course, at a speed tending to zero. This alone is the secret of decanting.

⁴⁶ In the Gier aqueduct, Lyon (France) one in every two manholes is larger to diminish water speed and facilitate decantation. These manholes had a sand settling basin.

LITAUDÓN, J. C. 2004, p. 81: *Les aqueducts antiques. Conduire l'eau (aquaeductus). Elementos de Ingeniería Romana. Libro de ponencias*. European Congress "Roman Public Works". Tarragona, November 2004.

Those who consider these basins as reservoirs do not take into account that the flow rate provided by the aqueduct (sometimes by many of them) was very high and very consistent throughout the year. These basins have only rarely lower outlets for draining and cleaning purposes, but not for the use of stored water, which would also be full of decanted mud. This type of premises are due to the traditional lack of participation of competent engineers in this domain. This is also the reason why sometimes the capacity of Roman hydraulic technique has been assessed at a level below its real achievements.



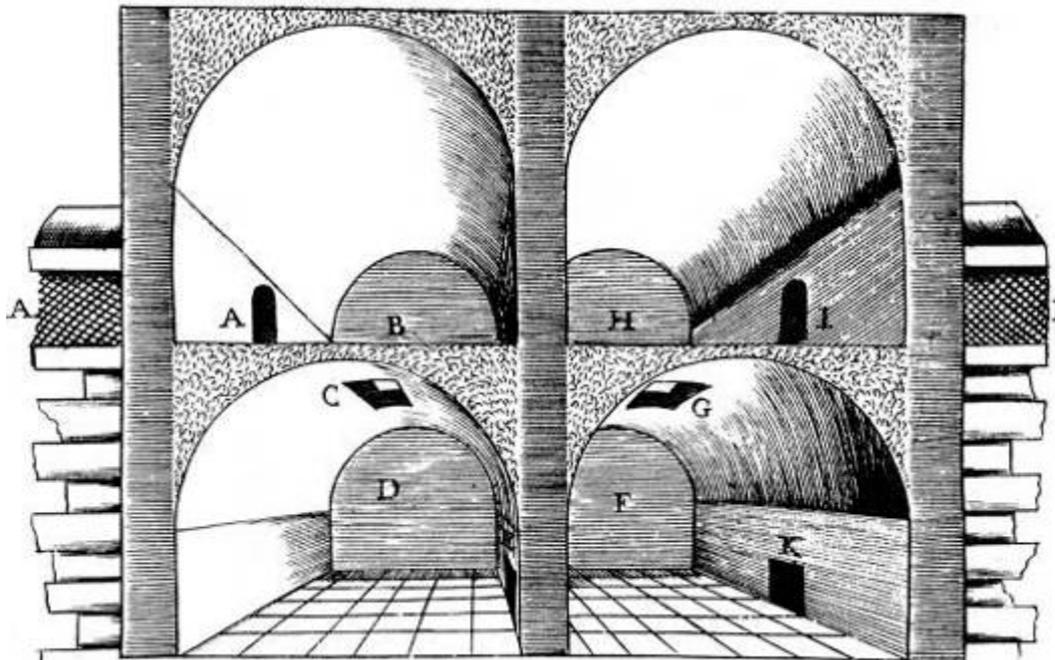
Overview of the large settling chambers in Carthage (Tunisia). Photo: J. C. Litaudon.



Interior view of one of the settling chambers in Carthage (Tunisia). Photo: J. C. Litaudon.



Chamber of the large basin of Vxama (El Burgo de Osma-Soria), constructed of concrete (*opus caementicium*) with a semi-toroid shape.



Reproduction of a settling basin, as described by *Vitruvius*, in one of the first printed editions of this work.

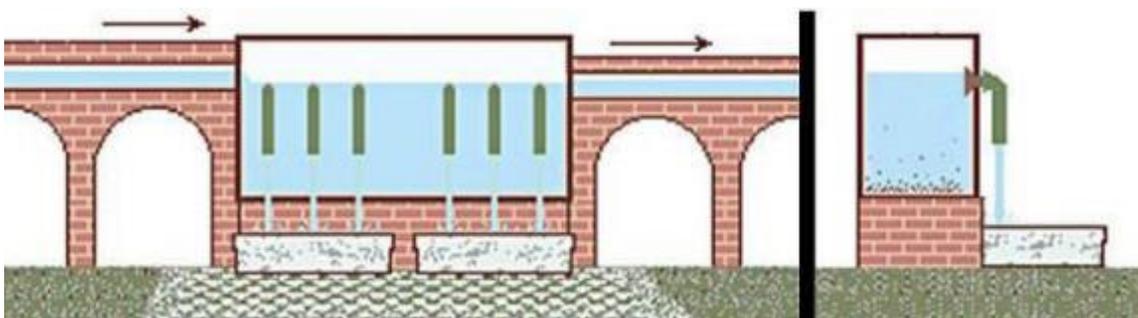


Roman basin following the scheme described by Vitruvius. It is located on the Fourvière hill in Lyon.

Therefore, the regulation of flow rates hardly existed in most drinking water supply systems to Roman towns. Water caught from springs reached the decanter, there it was cleaned, then it left the decanter to be distributed through a pipeline and finally it arrived at public fountains and final consumption points. At the end a volume almost equivalent to the one that entered the aqueduct reached the sewerage system.

Water needed to have an outlet in non-peak hours, when the taps of the houses were closed or when public baths closed. Although the flow was constant to the pools of the baths, technicians could decrease the flow during non-peak hours, closing valves.

At night, the spillways of the distribution network operated at maximum. At some point, when the channel's water level exceeded certain limits due to a low consumption rate, the channel sent water directly to the sewers. However, the large number of fountains arranged in town also fulfilled that role. Moreover, these fountains also undertook an additional mission that was not less important than to secure consumption, mentioned by *Frontinus* in his writings: to thoroughly clean the sewer systems.



Fountain installed next to a settling chamber, which is at the same time an intermediate spillway in the aqueduct.

But, did Romans actually store water in some cases? We should pay attention to these words of Pliny⁴⁷:

"Physicians investigate what types of water are the most suitable for consumption. They rightly condemn those that are stagnant and immobile, whereas they consider the best ones those that flow, that are purified and improve through their course and through agitation. Therefore I am astonished that some people give their enthusiastic approval to water that comes from cisterns. Physicians recognize that water from cisterns is inadequate for the stomach and throat for its hardness, and that it contains more slime and more disgusting insects than other water types".

We do not know for sure if in any particular cases people resorted to water storage, for example when water was scarce and/or the flow rate at the catchment areas had very marked seasonal variations. This possibility has not been adequately studied. So far, archaeologists have been content with thinking that all Roman basins connected to an aqueduct were reservoirs, when actually that almost never happened.

Thus, and according to this new point of view concerning the Roman's management of water supply flow rates, we will not find many cases of deposits that could be considered reservoirs (regulating basins). Most of what has been considered so far as reservoirs are actually mere settling or distribution basins, including both the large and the small ones.

The cisterns of Constantinople represent real regulating basins and water stores. However, they cannot be considered a work of Roman engineering, for they belonged to periods of the Late Antiquity or the Early Middle Ages. Amongst the many cisterns that were built in the city (under Justinian in the 6th century), that of Yerebatan or House of Medusa excels. It had a capacity of 80,000 cubic meters.

⁴⁷ Pliny the Elder (XXXI, 21, 31, 34): *Natural History*.



Cistern of Yerebatan or House of Medusa. It is a remarkably large water basin from the time of Justinian, in Constantinople. Istanbul (Turkey).

The need for these large-sized cisterns was a result of the successive sieges that the city suffered during unstable periods, the deterioration of its legacy of imperial aqueducts, largely due to the technological decline that prevented the provision of new aqueducts or the repair of those that were destroyed. The Yerebatan cistern itself was built with the rubble of the formidable pagan monuments, which were condemned by Christianity, but built with an almost dead scientific and technical level, as dead as the rest of the science and the lifestyle of the *Roma Aeterna*. The first great epidemic of the Black Death known in Constantinople, is coeval with the construction and use of these deposits. Thus, this is to give the starting signal for the technical-scientific medieval misery at the time when the Roman sanitary engineering died, not being surpassed until the present day.

Indeed, the storage of the already scarce water volumes left the huge sewer system of Constantinople in a bad sanitation condition, becoming a giant rat's nest, and a great breeding ground for the spread of the bacteria *yersinia pestis*. Rats and their fleas infected humans with the dreadful disease that came to decimate Europe's population for centuries.

Distribution

Starting from the settling basins, a large network of lead pipes of different sections and volumes distributed water to all city destinations.

With respect to the stale myth of lead pipe toxicity and its influence on the health of the Roman population, it should be noted that lead pipes are only relatively toxic for humans. It is much more pernicious not to have potable water.

Romans knew the lead pipe issue perfectly. According to *Vitruvius* VIII, 7: "*Water is healthier if it is conveyed by tubuli (ceramic) than by fistulae (lead). The reason is that lead pollutes water because it produces white lead, which seems harmful to health*".

In fact, lead contained in pipes may be partially dissolved in water. However, in hard water with some lime content, lead binds with carbonate and will then form a layer of lead carbonate, which is hardly soluble. This layer functions as a protective coating for the pipe's lead. Furthermore, under normal conditions (20° C and low pressure) lead does not react with water. However, when lead is in contact with moist air, reactivity with water increases. To do this, Romans provided pipes with air extracting valves (suction pads) that prevented air from resting in the lead pipes.

The main targets in water distribution, according to *Vitruvius*, were in this order: Public fountains, baths and finally private homes. Almost all Roman cities had sufficient water flow to meet these primary needs and even other secondary ones, as watering gardens and street cleaning, as indicated by *Frontinus* in his writings. In the case of individuals (for houses), water was distributed once an authorization was granted, together with the payment of a fee.

The complex distribution network that followed settling basins was structured around distribution hatches where pipes of different diameters (*quinaria*) were connected and distributed water to different concessions, fountains, baths, buildings and other places having the right of water supply.

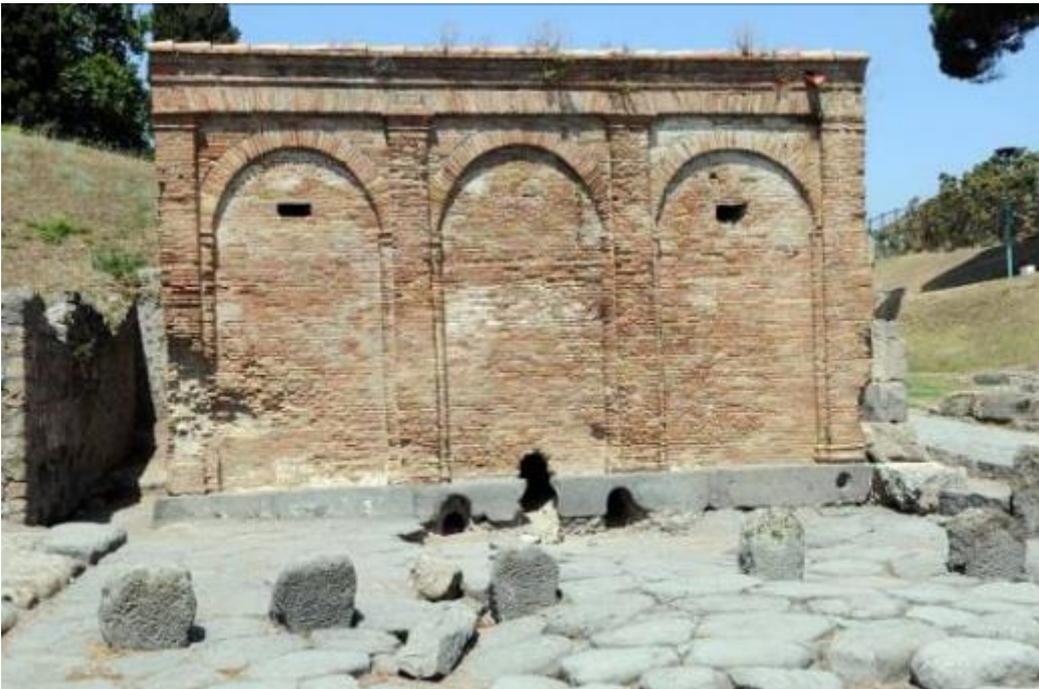
Illegal diversions of the precious liquid took place within this complex distribution network. A number of officials had to ensure that this did not happen, while others, the plumbers, were responsible for this misuse. *Frontinus* devotes several paragraphs to complain about illegal inlets in distribution hatches and about the disorder that reigned as to this issue, reporting on the culprits, at the beginning of his post as water administrator in Rome⁴⁸: "*A second discrepancy is due to the fact that an amount of water is caught at the inlet basin, another, remarkably smaller, is related to the hatches, and finally the smallest one lies at the distribution level. The cause of this discrepancies is the fraud committed by plumbers, whom I have caught diverting water from public pipes for the benefit of individuals. But also most of the owners of land, through which the aqueduct passes, bore the channel structures, interrupting their regular course benefitting individuals or their gardens.*"

The complexity of this network of pipes did not differ much from what we can find today in the water distribution network of our cities. Valves appeared very often at strategic points, with a whole range of typologies and a remarkable effectiveness. They were generally made of bronze and, like today, they were in charge of opening or closing the conduit water flow, at convenience.

⁴⁸ FRONTINUS. *De aquaeductu urbis romae*. LXXV.



Distribution chamber of the *castellum divisorium* of Pompeii. A water parting element distributes the water to the three different uses described by *Vitruvius*, setting a specific outlet height for each.



Exterior of the water distributor of Pompeii. You can see the holes through which the three pipelines departed, once the water inside was distributed.



Distribution chamber in the *castellum aquae* of Nemausus (Nîmes). The calibrated holes distributed the water flow to the various districts of the Roman city.

Various examples of joints and special connection fittings have been found. Air extraction valves in the upper parts of conduits, the so-called suction pads, did already exist and were as effective as they are today.

Finally, the design and manufacturing standards of elements such as fountain pipes, pool pipes in public baths and water taps in houses led to a wide range of fine products combining efficiency and beauty.



"Suction pad" or air extraction valve. Romul Gabarró Collection.



Roman flow interruption valve. Turned and machined with great precision. Romul Gabarró Collection.



Amphora used to form a 90° joint in an urban conduit of *Arelates*. Museum of Ancient Arles.

When water distribution networks were developed in towns located on hillsides of a certain extension, excessive pressure on the pipes was avoided in the lower parts of town: If the elevation difference between the distribution tank on top and the lower parts of the town was very big, the pressure on the system was modulated in a way that pipes never had to withstand excessive pressures.

Everything suggests that this pipe pressure within the urban area never surpassed more than one atmosphere, that is, ten meters of water height. The positioning of intermediate distribution basins in Spanish cities like Bilbilis, Uxama, Segobriga, Valeria, etc., confirms that the pipe network was never subject to pressures higher than the said value.

It is worth mentioning the Roman city of Bilbilis as a paradigm of the lack of knowledge on water supply systems to Roman towns. It has a large and complex system of distribution basins located on the hill on which the city was built. The system clearly indicates a high level of water consumption due to the existence of several public pools at its highest point, just out of reach of most of these basins. This leads to conclude that there was an abundant water supply from outside, in this case through pipelines coming down from a spring from the nearby mountains. Although the basins are installed on the crests of the hill (which were useless for rain water collection) and the area has a rainfall of 300 mm / year, many people have insisted on the idea that water supply in Bilbilis came from rainwater stored in these reservoirs⁴⁹.

⁴⁹ MARTÍN BUENO, M. 1975. pp. 205-222: El abastecimiento y distribución de aguas al Municipium Augusta Bilbilis. *Hispania Antiqua* V. Valladolid.

Today, we already know of the existence of at least one basin, over a distant hill, five meters higher than the most elevated point of Bibilis itself⁵⁰. This confirms the existence of a siphon system supplying the city from outside.

Even much more significant than this point is the considerable number of intermediate elevated deposits, whose remains can be analyzed in Pompeii, which are distributed across several areas of the city.

These deposits were used to break the pipe pressure, avoiding an accumulation of network pressure from the upper to the lower parts. They also distributed water to new destinations using new calibrated pipes (calix).

Pompeii deposits were located on pillars whose height did not exceed five meters and allowed to arrange the distribution system using sub-networks subject to a maximum pressure of half an atmosphere.



Interior view of basin located on the hill of Mora, one kilometer north of the Roman town of Bibilis.

⁵⁰ According to the information of José Juan Hernando of Calatayud.



Supporting pillar of a raised secondary distribution basin in Pompeii.



The water flow surplus generated between the inlet and outlet of the secondary distribution basin was often used to supply one of the various city fountains.



Calcareous deposits on the wall of the secondary reservoir's supporting column, originating from water dripping from leaks.



Imprints of supply and distribution pipes (now missing), from the secondary reservoir that was placed over this supporting column in Pompeii.

Wastewater conveyance

The transportation of water does not end in the final points of consumption. Wastewater coming from households, baths or latrines in urban areas, from irrigation fields, industrial

usage, laundering, tanning, etc. was conveyed out of the city through underground conduits, to be discharged into a river.

As it happens in modern times, there were toilets (latrines) in residential blocks and also in public places, in theaters, stadiums, baths, etc. An ingenious permanent drainage system, based on running water, eliminated waste immediately.

Water entered into the baths' pools permanently, thus it was renewed continuously. Once used, it was led to the sewer. Along with water coming from public fountains and other uses, the total volume of waste water equaled more or less the volume of supply water entering the city through the aqueducts. Rain water drained by street sewers was added to this water flow. The size of the needed final channel had been accurately calculated to cope with this contingency, and thus we find sewers of very large dimensions, which not only channeled these flows, but also allowed maintenance employees to pass through (which was absolutely necessary in the channels that carried many solid materials) and therefore were susceptible to cause problems due to flow interruptions. Consequently, a complex network of well-levelled channels was developed in the city subsoil to convey this water to the river. These channels had similar if not bigger problems than those that distributed water to the city, as a result of the urban development and building construction taking place over them.



Latrines in Ephesus baths (Turkey).





Vaulted sewer (*cloaca*) made of ashlars, in Cologne (Germany).

The topography

From a detailed observation and analysis of Roman water supply works that have survived to this day, we have deduced the collection and channeling techniques employed by the Romans, their structural features, materials used and their technical and artistic excellence.

These aqueducts worked for over three or four centuries with a high degree of efficiency, preserving the population's health and thus allowing the survival of a very advanced civilization in all fields of science. Actually it was science itself what enabled the existence of these channels.

The levelling works made for these channels, often several tens of kilometers in length, were considerably difficult in those times. Moreover, they would be equally difficult considering the optical topographical instruments of modern times.

The results obtained by the Romans in this domain are only possible through rigorous scientific levelling. Advanced topographical techniques must be known, as well as the shape of the planet Earth, its dimensions, and the influence that these have on the levelling of great

lengths⁵¹. In addition to this knowledge, precision instruments are needed to allow the collection of main altimetry data for the project and construction of the aqueduct, as well as to carry the necessary setting out works⁵².

Those who have had to undertake the setting out works of a long ditch know that it is a hard and necessarily repetitive task. You need to work in short stretches, progress carefully to avoid mistakes and repeat the itinerary several times to ensure the results, averaging the small errors that always occur.

If we extrapolate this work to a well-known real aqueduct, such as that of *Nemausus* (Nîmes), 52 kilometers long, where intakes are scarcely twelve meters higher than the destination basins in the city, knowing that the aqueduct runs through a broken terrain, we will be confronting an impressive challenge. Even current topographers would think twice before accepting such a task.

Basically, the following questions would be raised even before budgeting or starting with the aqueduct's project:

- How to determine whether the catchment areas in *Vcetia* (Uzès), were higher than in *Nemausus*, due to the small difference in height, for such a long distance.
- And once this is confirmed, how to determine the exact height difference that guarantees the channel's viability.
- Given that the channel's viability is at the limit (0.02% average gradient), how to undertake the necessary setting out works to accurately define the channel with such a shallow slope.
- How to know the actual water quality, as to its lime contents, which assures that the channel won't be choked too quickly by calcareous concretion.

And once engineers took the risky and brave decision to build the aqueduct, new problems arose:

- The channel had to be built with such a shallow slope, in a broken and rugged terrain, without making an error in the levelling process that could have disabled the previous work.
- It was necessary to build large banks in order to define a big channel section, for the channel's gradient and the low water speed forced this solution to maintain the required supply flow.
- The channel's large section forced to enlarge the supporting structures, including the arcades of the Pont du Gard, together with all excavation works and stonework.

However, the aqueduct was skillfully built and worked efficiently for at least three centuries.

⁵¹ MORENO GALLO, I. 2004, pp. 25-68: *Topografía Romana*. II Congreso Europeo Obras Públicas Romanas. Tarragona, octubre de 2004. Libro de Ponencias. Tarragona.

⁵² *Ídem*.

Other known aqueducts presented new challenges. Each was a separate case, sometimes easy to solve, other times it required a complicated solution.

The scientific knowledge needed for the successful undertaking of these works was inherited from previous civilizations. In the Greek world (and partly in the Egyptian world too) topographical knowledge already existed, which was useful for these tasks. Great aqueducts were built during the Greek and Hellenistic periods.

Eratosthenes had already determined very precisely the radius of the Earth, in the third century B.C. Thales, Pythagoras, Euclid, Hipparchus and Hero had developed trigonometric calculations transforming them into a very powerful tool for topographical survey work.

The influence of the earth's round shape in water surface level was known in Roman times, at least from Archimedes' postulate⁵³. It was already known that long measurements in levelling tasks caused the greatest errors. However, knowing as they knew the radius of the earth, as well as the sphericity error caused by horizontal measurements, they practised long night-visuals supported by lanterns, which allowed determining elevation increases with a lower error than when applying classical iterative levelling. These involved many seasonal changes and a significant accumulation of errors.

There were various instruments used for leveling water. The Dioptra is known to be used for levelling purposes but, as Vitruvius himself announced, for precise levelling a chorobates was used. Both instruments have been object of an analyses and interpretations over the centuries, as only a few classical texts described them vaguely.

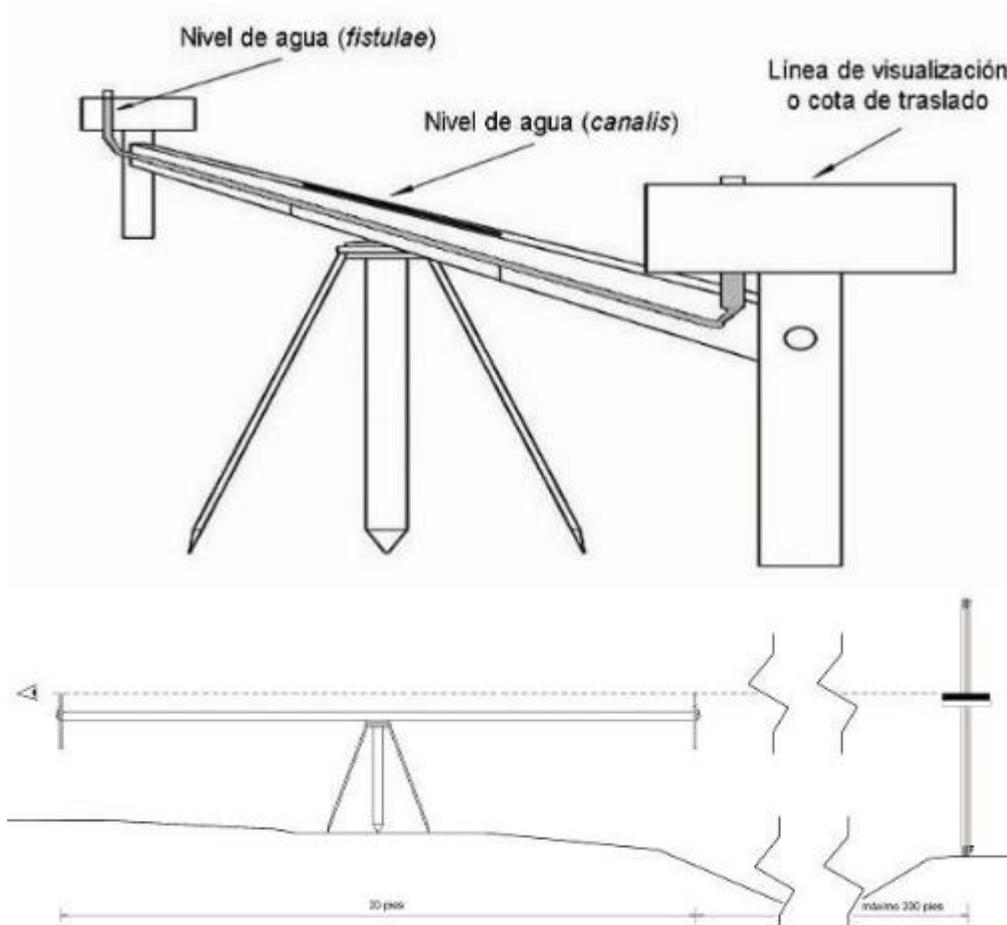
After ascertaining the little success of the reconstructions proposed to this day, with the production of totally ineffective devices, we have rebuilt both devices following the descriptions of the available classical texts. Thus, we found that both the Dioptra⁵⁴ (a true theodolite of antiquity) and the chorobates⁵⁵ had an admirable efficiency and precision, well up to the great challenges of Roman public works.

⁵³ Issue mentioned by VITRUVIUS: *De Architectura libri decem, liber VIII, ch. V, 3*: "Perhaps some reader of the works of Archimedes will say that there can be no true levelling by means of water, because he holds that water has not a level surface, but is of a spherical form, having its centre at the centre of the earth".

⁵⁴ MORENO GALLO, I. 2006, pp. 357-367: *Dioptra*. Nuevos Elementos de Ingeniería Romana. 3rd Congress of Roman Public Works. Astorga, October 2006. Book of Lectures.

⁵⁵ MORENO GALLO, I. 2004, pp. 25-68: *Topografía Romana...* ob. cit.

The Roman and the modern levelling instruments (the latter equipped with optical elements), have been subjected to different tests. The result has been that both showed a comparable accuracy, the both of them being suitable to accomplish the most difficult levelling tasks, as the ones that have been mentioned further above.



Operation scheme of a chorobates described by Vitruvius. Reconstructed, tested and patented by us in 2004. “The chorobates is a straightedge about twenty feet long. At the extremities it has brackets, made exactly alike and jointed on perpendicularly to the extremities of the straightedge”. VTRUVIUS: *De Architectura libri decem, liber VIII, cap. V, 1.*

The setting out works (and instruments) of the aqueduct tunnels were introduced through the entrances and manholes (*putei*) that also served for their excavation. Once within the tunnels, the alignments were defined in both directions until they met the alignments corresponding to the next manholes. The galleries’ alignments had to meet at the intermediate point between manholes. Although there could be some deviation in the horizontal alignment, errors in vertical alignment were considered unacceptable, for they could lead to a bad hydraulic performance of the channel.

From the examination of the galleries that we know, it is easy to deduce that planimetric errors were very frequent. The romans did not care too much about the tunnel’s planimetric alignment because it was well known that it could be easily remedied.



Route rectification in one of the subterranean galleries of the aqueduct in Vxama (Burgo de Osma, Soria). The section that was uniformly excavated until this point, is diverted to the right to meet the stretch that started from the opposite direction.

Several European authors of the archaeological domain have studied this phenomenon⁵⁷. Typically it has been attributed to topographic errors, but knowing the expertise of Roman topographers, and the good judgment of aqueduct builders, other explanations should be found.

We have found that the tunnels of gold mining channels, in the northwest of the Iberian Peninsula, were excavated avoiding hard quartzite which is impossible to break with a pick. Soft rock or rock that was easy to break was constantly sought when excavating galleries in antiquity.

We also know that long aqueduct galleries like the one from Albarracín to Cella (Teruel), five miles long, never show a straight alignment between manholes, well away from the shortest path. However, there is an explanation for this. In that area, the aqueduct runs through massive calcareous terrain, where no clear stratification can be observed nor changes in the rocks constitution that may justify the alignment variations. The most significant fact is that in most of this stretch of the tunnel follows natural fractures of the rock. Obviously, it was easier to excavate the aqueduct close to that discontinuity, which acted as a weak area where the rock could be broken more easily, enabling a faster and easier excavation work.

⁵⁷ GREWE, K 1998: *Licht am Ende des Tunnels: Planung und Trassierung im antiken Tunnelbau* (Mainz).



View of the rock fracture that goes through the left gable of the excavated gallery and continues at the manhole's wall, in the foreground. Tunnel of the aqueduct from Albarracín to Cella.

It is true that other galleries smaller than the ones that we have just mentioned brought real headaches to their builders. There is even epigraphic legacy on this issue.

Such is the case of the aqueduct of *Saldæ* in Bejaia (Algeria), with only 482 m long. It needed the participation of an expert topographer, called *Nonius Datus*, to manage to meet two galleries that started to be excavated on either side of a hill. The story of his feat was printed on a *cippus*. Technical and topographical feats related to known Roman aqueducts are innumerable.

Roman aqueducts near 100 kilometers long exist in Cologne (Germany) and of 132 km in Carthage (Tunisia). More than 240 kilometers long was the one of Constantinople (Istanbul)⁵⁸. One channel of the many that provided water to the gold mine complex of Las Médulas (León) was 143 km long. The Médulas network exceeds 600 km. The aqueduct of Gier in Lyon was 86 km long, and the one of Brévenne had a length of 70 km within the capital. Those of Pergamon (Turkey), Arles and Nîmes (France), were around 50 km in length. Cherchel's (Algeria), Reims' and Beziers' (France) aqueducts were between 40 and 45 km long.

The average slope ratio of the Nîmes aqueduct makes an incredible 0.2 per thousand (20 cm drop per km); Carhaix (Brittany, France) and Pergamon aqueducts had a slope ratio of 0.3 per thousand and the aqueduct in Reims 0.5 per thousand.

⁵⁸ ÇEÇEN, K. 1996: *The longest roman water supply line*. Estambul, 267 p.

The siphon systems that were present in the four aqueducts feeding *Lugdunum* (Lyon) show incredible figures: The four siphons of the Gier aqueduct represent over 5 km in length; the double siphon of Yzeron is about 6 km long; The two siphons of Mont d' Or made almost 4 km and the same can be said of the only siphon existing at Brévenne.

Conclusions:

We still have to discover many Roman aqueducts whose features will amaze us again. Many of the techniques that Romans applied remain still unknown and hidden in the absence of a rigorous analysis of these works.

We still do not know if the elevation of water by mechanical means was common in Roman water supply. Despite the low profitability of this solution, particularly in a civilization whose technology allowed water to be led by gravity to incredibly high places, we have found large water reservoirs located tens of meters above the arrival height of the impressive Roman rock-cut channel in the Roman city of *Vxama*⁵⁹.

The relation between the various reservoirs that have been found and the different channels (whether known or unknown) has not been resolved in most Roman cities where at least some of the other elements of the aqueduct have appeared. In other cases, the location of the sources or the alignment of most of the channel has not been identified.

There is still no answer to any of these questions for the vast majority of Roman cities.

However, we believe that the problem relies on how these questions have been approached to this day.

Any new studies on Roman aqueducts (and, in fact, on all the Roman engineering domains) should be undertaken on the basis of the following premise: Only a high level of scientific and technological knowledge could allow the fulfillment of these achievements.

Therefore, an engineering approach in the analysis of Roman public works is deemed essential. Without this approach, we will never get to fully understand the Roman civilization.

⁵⁹ GARCÍA MERINO, C. 2006: *Avance al estudio del acueducto de Uxama*. Nuevos Elementos de Ingeniería Romana. 3rd European Congress of Roman Public Works. Astorga, October 2006. Book of Lectures.