Hydraulic engineering of inverted siphons in Roman age: a review

G. Temporelli and F. De Novellis

ABSTRACT

In this work the authors wish to present a technology, less known if compared with the Roman age arcaded bridges used to cross broad and deep valleys: the inverted siphons. These structures are very complex hydraulic systems: for their good functioning, in fact, not only adequate constructing tricks were necessary, but also good theoretical knowledge, to be applied during the planning stage. In particular the systems that will be examined in this work are the double inverted siphon of the Yzeron aqueduct (Lyon, France) and the triple inverted siphon of Aspendos (Turkey); in both cases the Roman engineers ensured the correct functioning of the systems relying on specific technical solutions. Besides, the Barratina (Termini Imerese, Italy) siphon will be shortly presented, that is a "mixed" siphon whose technical conception distinguished it from the others. The Barratina siphon is the only case so far known in the history of the Roman aqueducts where the receiving tank is above the hydraulic grade line; nevertheless in many cases a precise leveling was not executed. It still possible that in the territory of the Roman Empire, other similar solutions can be found.

Key words | Aspendos, inverted siphon, Roman aqueduct, Termini Imerese, Yzeron

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INTRODUCTION

Every society has left traces of its own history: in particular, from the Roman age there are many records over the whole territory belonging to the Empire. Many of these survived to the Medieval and Renaissance ages, from wars, from vandalism and natural wear over centuries, until present time, as proof of the greatness of some of these works. In addition to the writings of illustrious authors such as Frontinus and Vitruvius, it is thanks to the analysis of these discoveries that it was possible to better understand the level of technical and theoretical knowledge in the Roman age.

The aqueduct system relied upon gravity for its operation; the water was collected from natural springs whose flow rate was constant enough all over the year. The aqueduct ran mostly underground through conduits bored with the trench technique or directly in solid rock, in both cases, well protected from the outside (Loffi 2007).

When the channel reached a valley, the Roman engineers could follow the contour line of the hill slopes or build either an arcaded bridge or an inverted siphon. The choice was taken considering the characteristics of the valley: when the depression was either too broad or too deep (more than 50 m), the siphon was preferred (Mantelli & Temporelli 2007). Unfortunately only few finds of the ancient inverted siphons survived to modern-day: while that is the case for parts of the masonry works, lead pipes were reused in following epochs for technological and military fabrications, leaving just a few examples (sometime just fragments), now exhibited in museums.

Inverted siphons represent for sure the most complex technological part of the Roman aqueduct for the problems presented both in the start-up phase and during the normal functioning; they are in fact at the same time necessary and extremely critical because they can compromise

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the functioning of the entire distribution system in case of anomaly.

HYDRAULIC SCHEME OF SIPHON AND INVERTED SIPHON

The siphon

A siphon is a continuous tube that allows liquid to drain from a reservoir through an intermediate point higher than the reservoir itself, the flow being driven only by the difference in hydrostatic pressure without any need for pumping. It is necessary that the final end of the tube be lower than the liquid surface in the reservoir (Figure 1).

Liquids can rise over the crest of a siphon because they are pushed by atmospheric pressure.

Once started, a siphon requires no additional energy to keep the liquid flowing up and out of the reservoir. The siphon will pull the liquid out of the reservoir until the level falls below the intake or until the outlet of the siphon equals the level of the reservoir.

The maximum height of the crest is limited by atmospheric pressure, the density of the liquid, and its vapor pressure. When the pressure exerted by the weight of the liquid equals that of atmospheric pressure, a vacuum will form at the high point and the siphon effect will end. The liquid may boil briefly until the vacuum is filled with the liquid's vapour pressure. For water at standard atmospheric pressure, the maximum siphon height is approximately 10 metres.

Of course, 10 metres is a theoretical value that does not consider real conditions where frictions cause the value to be less because of load losses. Moreover the well-functioning of the siphon is also affected by air pressure, therefore by altitude: functioning decreases with an increase of altitude.

The inverted siphon

The inverted siphon, so called because it presents an opposite concavity with respect to the siphon, was largely used in Greek and Roman aqueducts and is still considered of interest by modern engineers and architects.

Water was carried across the valley under pressure in a closed pipeline; the material used to manufacture the pipes might be lead, stone, and ceramics/terracotta; it was chosen considering the availability of raw materials and the pressure that pipes had to withstand.

Next to the valley, water, arriving by means of a conventional aqueduct channel, was collected in a storage tank (header tank) and crossed the valley through a piped conduit descending on one side to the bottom of the valley and ascending up the other side to the receiving tank, from where the water was fed into an aqueduct channel again. Because of load losses, the receiving tank had to be placed to a lower level than the header tank. Usually the lower part of the valley was cut off by an arcaded

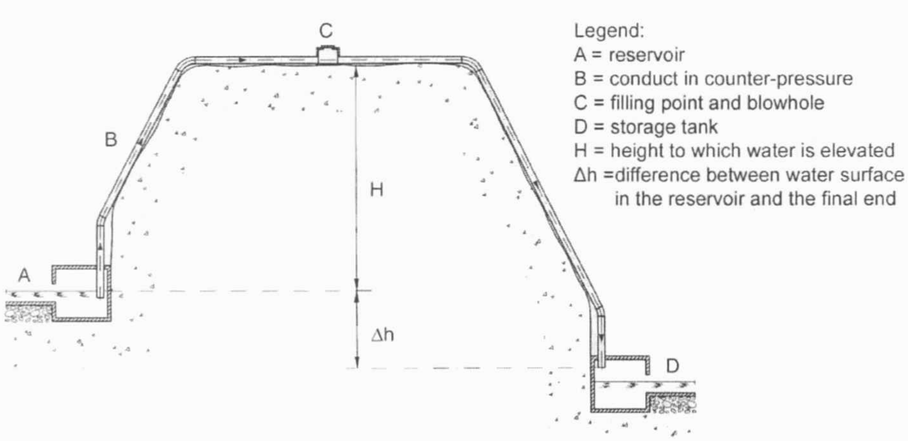

Figure 1 | Scheme of a siphon.

bridge (*venter*) on which pipes laid down so that the river in the valley could pass below without damaging the aqueduct (Figure 2).

This system does not present theoretical limits for its use, nevertheless the high intensity of the hydrodynamic and hydrostatic stresses requires an appropriate selection of materials and an advanced and detailed projecting phase that considers the different problems as, for example, the territory morphology.

General and specific problems of functioning

In this part are listed the main anomalies and functioning problems that may arise during the start-up or the normal functioning of an inverted siphon.

- Presence of air: the presence of air in a pressurized conduit can hinder, partially or totally, the water passage, compromising the normal functioning. Vitruvius, knowing the possible malfunctioning due to the presence of air, mentions the *colliquiaria*, a system to be installed in the lower part of the siphon in order to let air come out if necessary.
- Hydrostatic pressure: pipe breaks due to hydrostatic pressure can be avoided using pipes made with proper materials and a correct thickness. The use of multi-leg siphons is also useful to reduce pressure in pipes.
- Water hammer: is a pressure surge or wave resulting when a fluid in motion is forced to stop or change direction suddenly. Water hammer commonly occurs when a valve is closed suddenly at an end of a pipeline system. The intensity of the water hammer is higher as the change in water velocity is more sudden. Roman pressurized conduit were also affected by this problem mainly not as a consequence of the opening and closing of valves but of fissures, present especially in inverted siphons made with stones, that let pressurized air escape, influencing water motion.
- Curves: a sudden change in direction causes an anomalous stress to conduit walls giving origin to fissures and detachments between joints, especially in stone manufactures; next to inverted siphons, vertical curves (uphill or downhill), and sometimes horizontal curves, are always present.
- Start-up: Vitruvian's cautions, related to the slow filling rate required in initiating aqueduct flow to avoid large force oscillation, are found in *De Architectura*–Volume VIII (Vitruvius 27–23 BC): "...The level of the pipes being thus adjusted, they will not be sprung out of place by the force generated at the descent and at the rising. For a strong current of air is generated in an aqueduct which bursts its way even through stones unless the water is let in slowly and sparingly from the source at first, and checked at the elbows or turns by bands, or by the weight of sand ballast ... ". Recent studies have pointed out and confirmed these problems, in particular for starting-up an inverted siphon.
- Hydraulic grade line: in case of multiple inverted siphons, air pockets might be formed just next to a rise, influencing the normal water flow.

In the following, three different hydraulic systems adopted by Roman engineers in order to avoid such problems are considered.

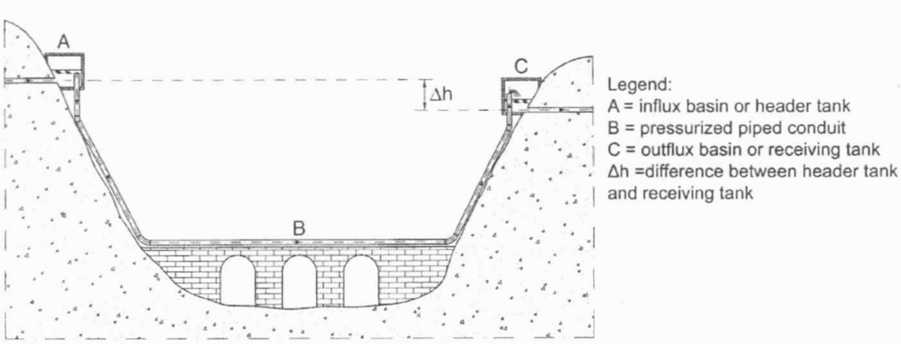

Figure 2 | Scheme of an inverted siphon.

THE DOUBLE INVERTED SIPHON OF YZERON

In the Roman age, four aqueducts delivered to Lyon about 45,000 cubic metres per day of spring water: Gier (15,000 m^3/day), Mont d'Or (6,000 m^3/day), Yzeron (13,000 m^3/day), and Brevenne (10,000 m^3/day). These aqueducts had in common the presence of inverted siphons with multiple lead pipes, used to cross broad and deep valleys; many parts of masonry works are still visible (Fassitelli 2002).

The Yzeron aqueduct, probably built under Augustus (20–10 BC), had to cross a depression 5 km wide and 90 m deep near Craponne where a hill was also present. Due to the morphology of the valley, the possibility of building an arcaded bridge was not taken into consideration while it was feasible to build an inverted siphon even if of considerable size. One of the problems that engineers had to face concerned the high pressure that could be reached in some points (approximately 9 bar); the problem was solved using a considerable number of parallel pipes with a small section (probably with a diameter of 10–12 cm) instead of a single larger pipe (Burdy 2008).

Another problem developed from the presence of the hill that hindered the water flow. Three main problems had to be taken into consideration:

- building a siphon with only one pressurized conduit might cause, next to the hill, gathering of air and therefore, in absence of a blower, the partial or total obstruction of the water flow;
- building a tank on the hill, being under the hydraulic grade line, might recall pressurized water and cause its discharge;
- the building of a subterranean conduit, even if it could appear as a good solution to obviate the above-mentioned problems, was certainly difficult to realize and manage.

In the end a different solution was chosen: Roman engineers decided to guarantee the continuity of the flow building an intermediate elevated tank that would take into consideration the hydraulic gradient. In Craponne a tank-tower was therefore built; it was 16 m high and supported by 14 pillars; only two pillars, the so called 'Les Tourillons' (Figure 3), are still visible.

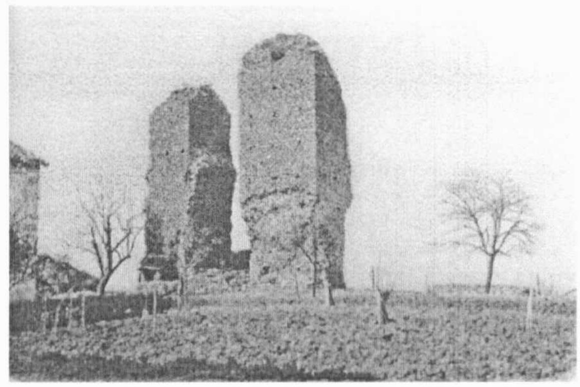

Figure 3 | The pillars of 'Les Tourillons' (Burdy 2008).

THE TRIPLE INVERTED SIPHON OF ASPENDOS

The ancient city of Aspendos, located about 50 km east of Antalya (Turkey), was an important commercial centre in Greek and Roman times for its central position along the north-south trade routes within western and central Turkey and its position on the Eurymedon River, which was navigable from the Mediterranean sea up to the city in classical time, making Aspendos an important sea port.

The aqueduct that served Aspendos was built around the II–III century AD. The aqueduct was fed by the spring complex of Gökçepinar, about 20 km north of the city; water was carried to the southern border of the Sariabali mountains by means of a conventional aqueduct channel, then crossed the 1.7 km-wide valley, between the mountains and the acropolis, by means of an inverted siphon (Kessener 2000). The pipeline of the siphon was made from about 3,400 perforated limestone blocks (Figure 4) measuring 85 × 85 × 50 cm, with a bore of 28 cm of diameter and sockets and flanges for proper joining sealed off with a mixture of lime and olive oil (Kessener & Piras 1998*a*).

Some of these blocks are equipped with a tunnel-shaped hole leading from the inside of the pipe to the outer surface, in some cases on the joint. These holes were normally closed off with stone plugs fitted with plaster. The purpose of these holes is not clear; it has been suggested that the holes served both to blow off if there was a dangerous pressure surge and enable the removal

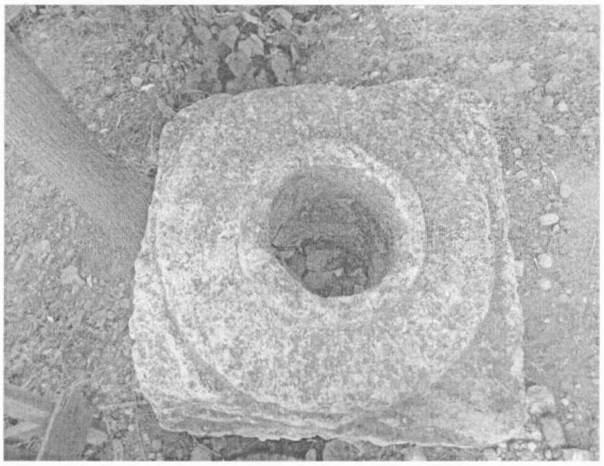

Figure 4 | Stone block of one of the Aspendos pipes.

of calcareous incrustation probably by means of hot vinegar (Caruso 2000).

Unlike Yzeron's siphon, in this case there is no hill along the path to justify the need for a hydraulic tower, nevertheless the Roman engineers took the decision to build two towers. The first tower, 40 m high, identified as the north tower, was built at about 600 m from the header tank; in this point the conduit bends of 16° (Figure 5); the second tower (south tower), 38 m high, lies about 900 metres south of the north tower, where the course bends of 55° (Kessener & Piras 1998*b*).

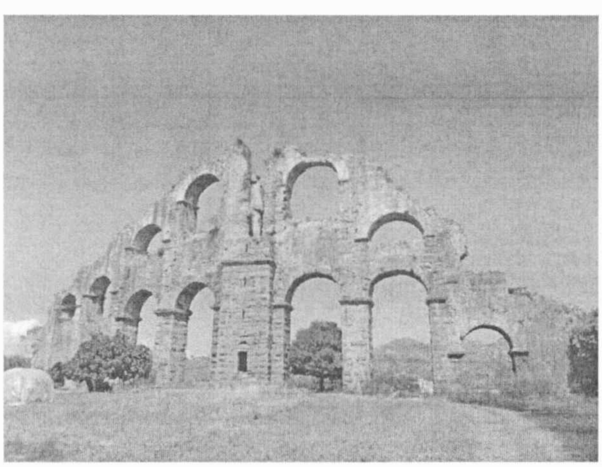

Figure 5 | North tower of the Aspendos inverted siphon.

Considering the visible remains, some reflections can be made on the reason why Roman engineers decided to build two hydraulic towers and consequently a triple inverted siphon. The upper part of the two towers has been destroyed, therefore no remains of the tanks placed on top arrived to modern days.

As previously mentioned, one of the major problems concerning the inverted siphon concerns the start-up phase. A recent analysis carried out by Ortloff & Kassinos (2003) with a simulation software (Computational Fluid Dynamics) has verified the hydraulic phenomena associated with the initial filling of the inverted siphon: in synthesis, it was demonstrated that, as a function of the initial flow rate, a water column oscillation is generated in the siphon ramifications that is slowly damped down by internal piping frictions due to the roughness of the material; nevertheless a breakdown of the conduit sometimes occurs.

The Aspendos tower basins may also represent an effective oscillation damping system functioning as accumulators.

Kessener (2000) also highlighted the utility of the two towers in damping/eliminating the negative effects (anomalous stress on pipes and water hammer) due to bends and air release from holes along pressurized conduits.

Aspendos towers are a unique case in the history of the Roman aqueduct and there is not certainty about the reasons for their construction. Nevertheless considering Vitruvius' work and the fact that he lived two centuries before the building of the Aspendos aqueduct, we can believe that Roman engineers knew all the problems concerning inverted siphons.

We are now going to analyze the accuracy of the hydraulic dimensioning of the Aspendos siphon thanks to modern knowledge in fluid mechanisms.

To determine energy losses due to water flowing into the siphon, it is necessary to calculate the friction coefficient of the internal wall of the conduit; this coefficient is dependent upon the hydraulic characteristics of the conduit and the water flow inside the conduit itself.

The hydraulic characteristics are represented through hydraulic roughness; in particular, relative roughness (dimensionless number) is computed by dividing the absolute roughness (given by the average height of the rugosity present on the internal surface of the pipe) by the pipe diameter. Therefore the relative roughness (r_{rel}) is express by the formula:

$$r_{rel} = \frac{r_{abs}}{D}$$

where:

r_{abs} = absolute roughness (mm)
D = pipe diameter (mm).

If we consider the Aspendos siphon, where r_{abs} is 4 mm because the conduit is made of raw stone, and D is 280 mm, $r_{rel} = 0.015$.

The Reynolds number (Re) is a dimensionless number useful to characterize different flow regimes. Reynolds number is defined as

$$\mathrm{Re} = \frac{\rho v D}{\mu}$$

where:

ρ is the density of the fluid (kg/m^3)
v is the mean fluid velocity (m/s)
D is the pipe diameter (m)
μ is the dynamic viscosity of the fluid (Pa s or N s/m^2 or kg/m s).

If we consider the Aspendos siphon, we have: $\rho = 1{,}000\,\mathrm{kg/m^3}$, $v = 0.65\,\mathrm{m/s}$ (calculated using the continuity equation: volumetric flow rate is given by the product of cross sectional area of flow and mean velocity–$Q = A \times v$), $D = 0.28\,\mathrm{m}$, $\mu = 0.0014\,\mathrm{kg/m\,s}$ (considering water at 20°C), and therefore Re = 130,000.

Note that when the Reynolds number is less than about 2,000 the flow is viscous and laminar; any roughness of the pipe is submerged in the viscous flow, and does not affect the head loss. On the other hand, for Re > 4,000 the flow is certainly turbulent, with increased losses. In this case the friction factor depends on the relative roughness of the pipe. This concept is also confirmed by the analysis of the Moody chart.

The Moody chart is a graph in non-dimensional form that relates the friction factor, Reynolds number and relative roughness for fully developed flow in a circular pipe. Knowing Reynolds number and relative roughness for the Aspendos system, from this chart it is possible to observe that the flow is characterized by a high turbulence and to determine the value of the friction factor: $\lambda = 0.043$. At this point we have all the information to work out head loss H_f (m) using the Darcy–Weisbach equation:

$$H_f = \frac{\lambda l v^2}{d 2g}$$

where:

H_f is the head loss due to friction
l is the length of the pipe
d is the hydraulic diameter of the pipe and is calculated as four times the cross sectional area divided by the wetted perimeter of the cross-section; it is important to note that the hydraulic diameter is not twice the hydraulic radius (for a pipe of circular section, hydraulic diameter equals the internal diameter of the pipe)
v is the average velocity of the fluid flow, equal to the volumetric flow rate per unit cross-sectional wetted area
g is the local acceleration due to gravity
λ is a dimensionless coefficient called the Darcy friction factor. It can be found from a Moody diagram.

For the Aspendos system we have: $l = 1670\,\mathrm{m}$, $d = 0.28\,\mathrm{m}$, $v = 0.65\,\mathrm{m/s}$, $g = 9.8\,\mathrm{m/s^2}$, $\lambda = 0.043$, therefore $H_f = 5.5\,\mathrm{m}$. This number represents the diffused head loss in the pipe and does not consider local energy losses due to change in pipe direction or in cross sections (inlet and outlet to tanks). Nevertheless, in this context local energy losses can be considered irrelevant.

Seen that the head loss usually expresses the energy loss due to friction at the walls of the conduit, it is possible to conclude that internal piping wall roughness is a key parameter to determine steady state flow rate and start-up oscillatory behaviour, as pointed out by Ortloff & Kassinos (2003). In particular, it is interesting to note that the wall roughness occurring during hand chipping manufacture corresponds to a friction factor optimal to limit start-up oscillation and to reach a steady state flow rate in a limited period of time; therefore the material chosen by Roman engineers, perhaps only by a stroke of luck, was optimal.

Considering that the difference of altitude between the header tank and the receiving tank is 14.5 metres, the calculated value of head loss shows that the system was able to let water flow without any particular narrowing. Note also that this difference of altitude could favour the flow of a higher quantity of water compared to the 30–40 L/s that probably fed the aqueduct. Such range was estimated on Gökçepinar springs thanks to a measurement carried out in the summer of 1979 (Fahlbusch 1987). Nevertheless, the slow filling rate had the beneficial effect of limiting start-up oscillations from developing and reducing forces on the piping.

To conclude the analysis on the Aspendos siphon, it is important to underline both the presence of the elevated tower open basins that acted as accumulators limiting oscillation from propagating into downstream branches of the siphon and the choice to build a multi-leg system to reduce water hammer effects and isolate segments that need repair.

THE BARRATINA SIPHON

In the Roman age, Termini Imerese (Palermo, Italy) was served by two aqueducts: Figurella (I century AD) and Cornelius (II century AD). Both aqueducts were quite limited (3,500 m and 7,100 m long respectively), but very interesting at the same time because they presented some important structures: arched bridges, inverted siphons, and a "mixed" siphon used in the Cornelius aqueduct to cross the Barratina valley (50 m deep and about 600 m wide). It is defined as a "mixed" siphon because the intermediate tank is positioned above the grade line giving origin to a double siphon: a first pressurized lead pipe connected the header tank with the intermediate tank while a second depressurized lead pipe, after a sudden change in direction, let the water flow from the intermediate tank directly to the city without a receiving basin (Figure 6).

The presence of an intermediate tank makes the Barratina system similar to Yzeron and Aspendos but at the same time the fact that the tank is positioned above the grade line, makes the Cornelius aqueduct unique.

The problems connected to this system are several:

- it is necessary to initiate the siphon;
- if air gets in the siphon, the water flow immediately stops;
- it is necessary to provide the system with blow off valves to eliminate air eventually present in the depression part of the siphon.

Due to the above problems, it is clear that questions can be raised about the choice of Roman engineers to have a "mixed" siphon with an intermediate tank above the grade line instead of a simple inverted siphon. A probable reason is given by the choice to reach the city crossing the flat country instead of following the steep slope of the valley avoiding the possible damages due to ground collapse. On the other hand if the tank was positioned at a higher altitude, it could be not necessary to realize an intermediate tank positioned above the grade line; in this case a longer pressurized lead pipe had to be used.

The solution adopted by the engineers in Barratina is therefore very difficult to interpret and as Belvedere (1986)

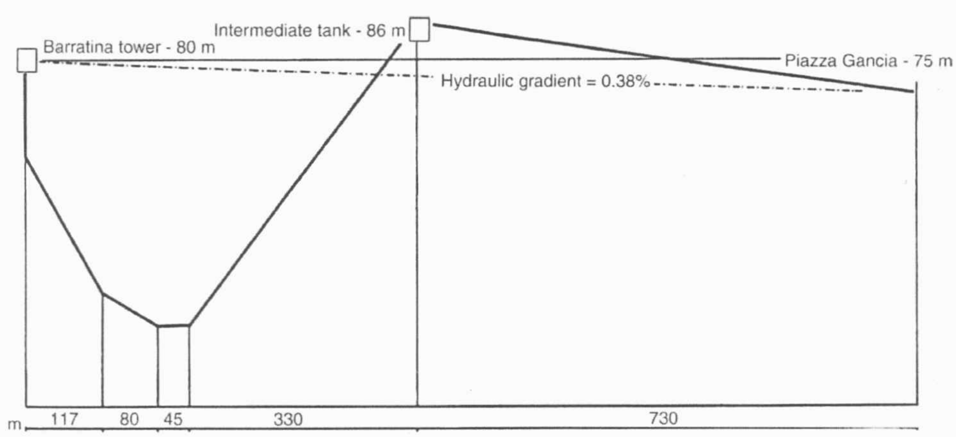

Figure 6 | Scheme of Barratina "mixed" siphon (Belvedere 1986).

suggested, probably Roman engineers did not completely understand the technical and operational difficulties that a "mixed" siphon could present.

CONCLUSIONS

Roman engineers became very daring in the construction of high arches to support the conduits across valleys and plains, but they also occasionally used complex systems such as the inverted siphon when structural and economical reasons led to this choice.

Yzeron, Aspendos and Barratina are three great examples of inverted siphons that have successfully functioned for several hundred years, demonstrating the high skills of Roman engineers in hydraulics applied to solving morphological problems of the territory. In particular the thorough study carried out by Ortloff & Kassinos (2003) on the Aspendos siphon also demonstrates the competence of Roman experts with regard to:

- materials: wall roughness occurring during hand chipping manufacture corresponds to a friction factor optimal in order to limit start-up oscillation and reach a steady state flow rate in a limited period of time;
- tower basins as oscillation damping systems;
- blowers as exit ports for air release;
- slow initial filling rate to eliminate pressure surges;
- multi-leg siphon to reduce water hammer effects and isolate segments that need repair.

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