Hypogea 2015

Proceedings of International Congress of Speleology in Artificial Cavities
Italy, Rome, March 11/17 - 2015

EDITORS

Mario Parise
Carla Galeazzi, Roberto Bixio, Carlo Germani

ISSUES CONCERNING ANCIENT ROMAN AQUEDUCTS

Leonardo Lombardi [1], Elettra Santucci [2]
[1] via G. Sacchi 20, Roma 00153 – leonardo.lombardi@libero.it
[2] via Rimini 16, Roma 00182 – elettra.santucci@yahoo.it

Abstract
During the realization of an aqueduct, Roman engineers had to solve many problems as the choice of the layout, the choice of the spring, the constant and regular slope, that could not be more than 1:1000 or, at maximum, 1,5:1000. In the cases the slope was higher they invented many systems to correct it with dissipation of the energy: dropshafts, stilling tunnels and stilling basins. Another problem was the realization of branches from an aqueduct, to serve a monument or a Villa, while the aqueduct was working. This contribution tries to explain the methods used in this period.
Keywords: hydraulics, roman aqueducts, water supply.

Riassunto
Nella realizzazione di un acquedotto gli ingegneri romani dovevano affrontare problemi legati alla natura del terreno, alla scelta della sorgente da cui captare le acque, problemi legati alla realizzazione di condotti con pendenze costanti e regolari, che non dovevano superare 1:1000 o, al massimo, 1,5:1000. Quando la pendenza era maggiore, inventavano diversi sistemi per la riduzione della stessa e per la dissipazione dell'energia: pozzi di dissipazione, gallerie di calma e bacini di calma. Un ulteriore problema consisteva nella realizzazione di derivazioni, che si distaccavano da un acquedotto per alimentare un monumento o una villa, quando l'acquedotto era in funzione. Lo scopo dello studio è di illustrare i diversi sistemi citati, il cui uso era diffuso nel periodo romano.
Parole chiave: *idraulica antica, acquedotti romani, approvvigionamento idrico.*

In this contribution we would like to focus on some issues, that are considered essential to understand the importance of the Roman aqueducts.
There is a moment in human history that dates back to different times in different regions of the earth; this moment coincides with the first agricultural settlements and the end or reduction of the gathering and hunting activities. In this "moment", that may last for thousands of years, plants for crops have been selected, and animals have been domesticated to get milk or meat. It is the beginning of the Neolithic, period with similar characteristics in different parts of the world, but occurring at different times, with a slow and continuous spread of discoveries. Only in the Americas, both in Mesoamerica and in South America, this moment occurs independently and in extended areas of the continent the AMH (Anatomically Modern Humans) changes from hunting and gathering to permanent settlement.
In the Middle East it occurs between 12,000 and perhaps 18,000 years ago, in Italy between 7,000 and 6,000 years B.P., and in the Americas 5,000 years ago. A common feature, in addition to agriculture and domestication, is searching for stable sources of water, if possible on the site of settlement. The first groups of people gather near springs and streams; then the research of rainwater storage systems developed, at the beginning with open basins and later with cisterns, and underground tanks of various shapes. With the increase of population, this was the most common solution used by all Neolithic civilizations and in the later stages also, the Metal Age, a phase that in Mesoamerica has never been reached. A big improvement was the construction of masonry tanks and the digging of wells, at first shallow, near waterways, on streams beds that during dry periods no longer had water on the surface, then, deeper.
But it is only less than three thousand years ago that ideas for the withdrawal of water from perennial sources developed, to carry water in areas that previously had none, through underground tunnels or open channels. This is the birth of the first aqueducts: qanats in Persia and channels in the Nile valley, are admirable examples. But even in the Etruscan culture and perhaps Villanovan also, ditches and streams were deviated and water was carried in urban areas and through agricultural areas for cultivation.
This was a great revolution that takes place in the area between the Tigris and the Euphrates. However, it was mainly in the Greek world that springs are intercepted and water transported, first to fountains next to the springs, then to more distant urban centers. In Italy, the first channels and tunnels of aqueducts are certainly Etruscans. The Romans learned and mastered these techniques. It is not a coincidence that the first Roman aqueduct, the Appius (326 B.C.), is an underground channel, and water was extract through wells and tunnels. The other Roman aqueducts are characterized by a scheme that could be called "Greek", even though the Romans developed, improved and most importantly spread throughout the empire the technique of aqueducts, that has been repeated over time until 1800, when the invention of extruded iron and cast-iron tubes and the invention of the first thermal and then electric engines, allowed to move in new directions.
The construction of the aqueducts to supply the city of Rome occurred over a long period of time, between the first aqueduct (the Appius) and the last one (the

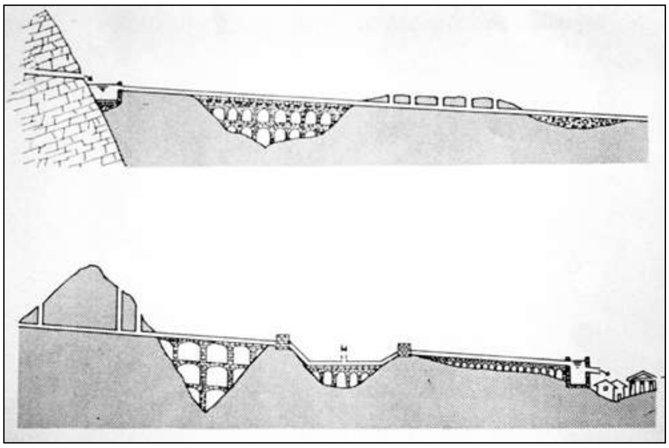

Fig. 1: scheme of an aqueduct (drawing C. Germani, after Dolci, 1958).
Fig. 1: schema di un acquedotto (grafica C. Germani, da Dolci, 1958).

Alexandrian) having passed almost 500 years.
There are very little data on aqueducts planning, the projects had to be a long and complex work: search of a source of water, estimation of its characteristics with observations which had to last years, such as the verification of flow rate, the choice of the optimal flow rate for sizing the channel, the location of the itinerary, and finally the fairly accurate assessment of the height of the start of the aqueduct (the incile) that had to be related to the height of the terminal tank in the city. All this issues represents not easy problems even today, despite the nowadays available topographic maps, aerial photographs and high-precision instruments.
In this work, we are not going to describe the aqueducts that over centuries have reached Rome. If we exclude the two almost entirely underground (the Appius and the Virgin aqueducts), the others all have similar characteristics. Figure 1 shows, in a schematic way, all the elements of an aqueduct.
The scheme shows how an aqueduct works and all its elements: the intake, typically connected to a specific reservoir for the deposit of solid impurities, arches, tunnels, siphons, and finally the terminal tank or castellum with pipes that reached directly the consumptions or reached secondary tanks and sometimes even tertiary tanks.
Frontinus writes that in Rome there were 247 castella and 630 including fountains, pools and basins. We should make some clarifications about terminal tank and, in general, all tanks. On the side of big tanks there were always small rooms, which we call control rooms, where there were often stairs to access the reservoirs but, above all, there were control valves to interrupt and/or regulate the water flow from the pipes connected to the tanks. These rooms are almost never taken into account by those who study reservoirs.
A good example is shown in a drawing, made by an Anonymous (Anonymous Destailleur) lived in the first half of the XVI century (Fig. 2), depicting with many details the so-called Botte di Termini, the main tank of the Baths of Diocletian in Rome.
It is a large tank (capacity at least 5000 cubic meters) with a flat roof sustained by 47 pillars. The most interesting element is a small room, separated from the reservoir and certainly locked to prevent theft or unauthorized access to the tank. In this room there was the service staircase for maintenance of the reservoir and a single valve, or many valves, to open, close and regulate the water flow (Fig. 3).
A tank without a closing valve, which is contained in a particular room or connected directly to the outlet pipe, cannot perform its function of accumulating water for withdrawals during the moments of maximum consumption. Even today, the tanks of the aqueducts perform this function, covering the morning and other times of the day consumption, when large amounts of water are used, with a night-time storage.
Another example comes from the Baths of Caracalla (Lombardi, Corazza, 1995), where next to the eighteen tanks, all linked together, which made it possible to have a volume of about 10,000 cubic meters, there were two control rooms with related valves, that were used to control the water flow to the dozens of pools and fountains of the Baths (Fig. 4).
As concerns the eleven aqueducts that reached Rome, there is an extended bibliography that ranges from Frontinus to Fabretti, Ashby, and more recent works

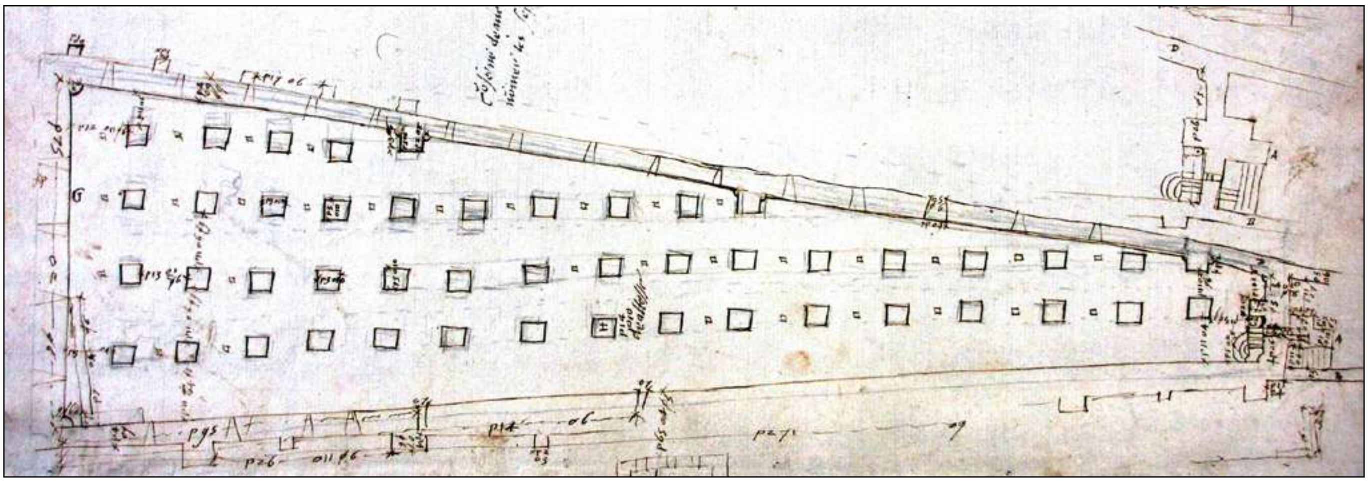

Fig. 2: "Botte di Termini" by Anonymous Destailleur (Berlin State Museum Art Library).
Fig. 2: Botte di Termini da Anonimo di Destailleur (Biblioteca d'Arte del Museo di Stato di Berlino).

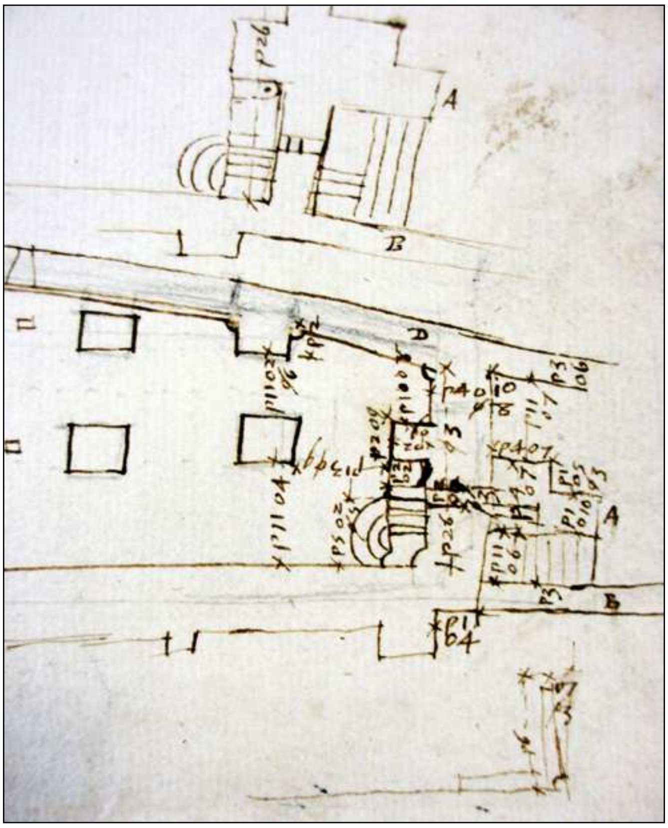

Fig. 3: control room of "Botte di Termini"(detail of the previous drawing).

Fig. 3: camera di manovra della Botte di Termini (dettaglio del disegno precedente).

that indicate, sometimes approximately, the routes and final destinations of the aqueducts.

The tables 1 provide all the data to have at least a rough idea on the aqueducts that brought water to the city. In the tables, restorations and modifications for repairs or changing of the itinerary are not mentioned. The tables show us the framework of the Roman aqueducts, with dates of building and the main areas of origin, useful data for both channels altitude and water's characteristics (waters from the Subiaco area and the Aqua Alexandrina are harder than those from the volcanic areas).

Table 2 shows valuable information: first, the comparison between elevations at the source and in the city, related to the length of each aqueduct. Elevations indicate that the gradient of the channel and speed reached by water, without appropriate corrections, exceeded slope and speed that Roman engineers considered optimal. The channels should have a maximum gradient of 1 or 1.5 meters of altitude loss per 1000 meters of length. Lower slopes favored the development of vegetation and deposits of calcium carbonate; higher slopes were dangerous since they determined the increase of speed and energy of the water, with possible damage to the structures. The water flow speed had to reach at maximum one meter per second. As we will see, in many parts of the aqueducts these parameters exceeded.

To realize the aqueducts and to get all the data needed for their construction, the Romans possessed quite efficient tools. For making alignment they used the groma, an instrument consisting of a pole, supporting an articulated cross arm, with four plumb lines hanging, that was used by sighting in the direction of the chosen route (Fig 5).

Along the route stakes were fixed, until the end point of the planned route was reached. This instrument was used in both flat or hill terrain. If the relief was not too high, wells were excavated, whose bottom reached the future tunnel. Later, probably, portion of tunnels between wells were dug, with a first exploratory tunnel

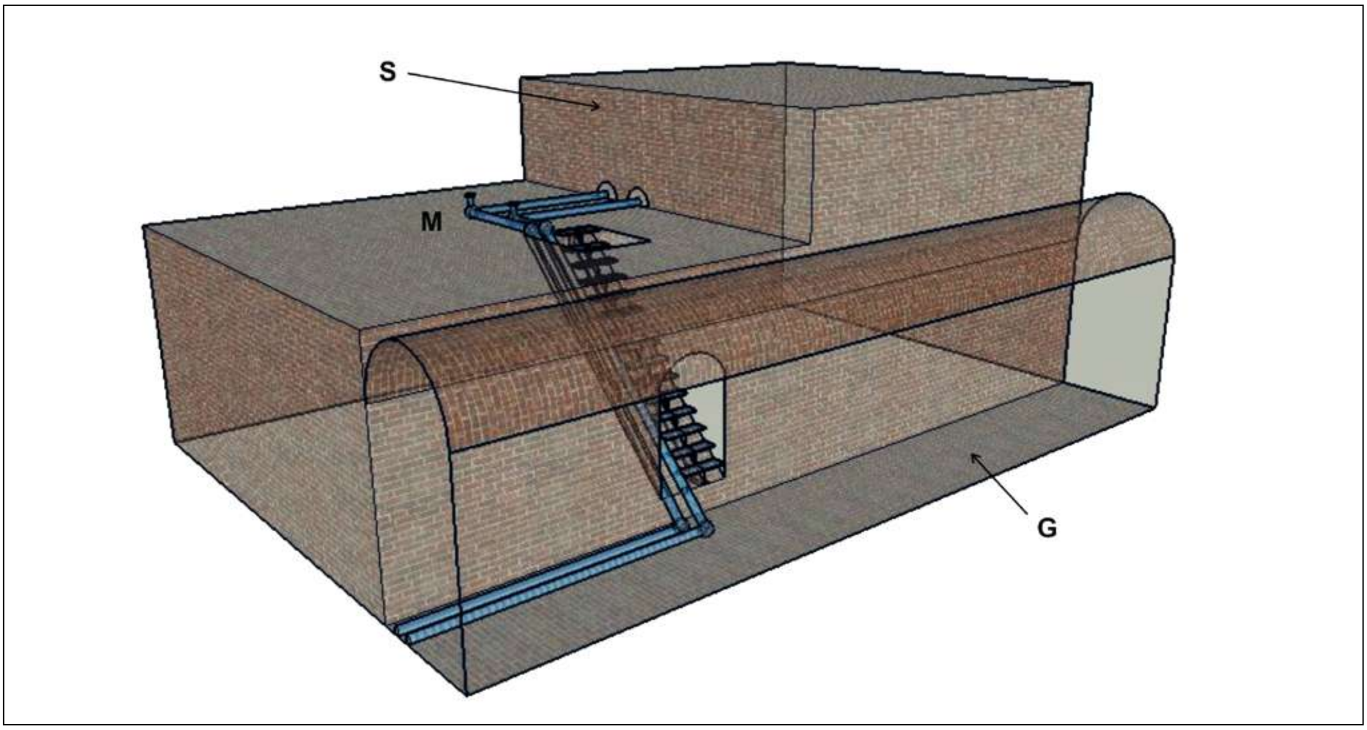

Fig. 4: Tanks and control room of the Baths of Caracalla (after Lombardi, Corazza, 1995).

Fig. 4: Serbatoi e camera di manovra delle Terme di Caracalla (da Lombardi, Corazza, 1995).

Aqueduct	Date of building	Acquifer	Flow rate (l/s)
Aqua Appia	312 B.C.	*Volcanic - Colli Albani*	876
Anio Vetus	272 B.C.	*Water flowing - Aniene*	2.111
Aqua Marcia	144 B.C.	*Limestones - Sublacense*	2.251
Aqua Tepula	125 B.C.	*Volcanic - Colli Albani*	192
Aqua Julia	33 B.C.	*Volcanic - Colli Albani*	386
Aqua Virgo	19 B.C.	*Volcanic - Colli Albani*	1.201
Aqua Alsietina	2 B.C.	*Volcanic - Sabatini*	188
Aqua Claudia	52 d.C	*Limestones - Sublacense*	2.111
Anio Novus	52 d.C	*Water flowing - Aniene*	2.274
Aqua Traiana	110 d.C	*Volcanic - Sabatini*	1.368
Aqua Alexandrina	226 d.C.	*Volcanic - Colli Albani*	254
		Total l/sec	13.212
		Total square meters/day	1.117.735

Tab. 1: list of the Roman aqueducts, execution date and area of origin.
Tab. 1: elenco degli acquedotti, data di esecuzione e area di origine.

Aqueduct	Date of building	Elevation at source (m a.s.l.)	Elevation in Rome (m a.s.l.)	Total length (km)	Slope percentage (per 1000)
Aqua Appia	312 a. C.	25	12	16,695	1
Anio Vetus	272 a. C.	300?	43	63,640	4
Aqua Marcia	144 a.C.	317	55,70	91,375	3
Aqua Tepula	126 a.C.	256	57,61	10	20
Aqua Julia	33 a.C.	350	59,37	13	23
Aqua Virgo	19 a.C.	23	18	19	0,2
Aqua Alsietina	2 a.C.	160	8	32	4,6
Aqua Claudia	52 d.C.	320	63,88	53	4,9
Anio Novus	52 d.C.	264	65,99	86	2,5
Aqua Traiana	110 d.C.	300	73	60	3,8
A. Alexandrina	236 d.C.		48?		

Tab.2: list of the Roman aqueducts, execution date, elevations, slope percentage.
Tab. 2: elenco degli acquedotti, data di esecuzione, quote, pendenze.

that was later enlarged to the project size.
In particular cases they used a different instrument, the *dioptra* (Fig. 6).
This consisted in a movable disk on which angles and directions of cardinal points were marked.
Sighting in the viewfinder established the exact direction and, in this case also, they proceeded marking the ground with stakes, before starting the excavation of wells and tunnels. The dioptra, that is attributed to the Greek scientist Heron of Alexandria, author of numerous inventions and discoveries, also worked for vertical measurements, actually representing a sort of old theodolite.
For the control of gradients a long level, the corobate (Fig. 7) was used: through a channel filled with water, it allowed to appreciate level differences with approximations lower than a millimeter. Plumbs and adjustable foot made it possible to place the level in a perfectly horizontal position. To correct errors of slope, they used application of different thickness of *cocciopesto* and then checked that the finished floor had the right slope to let the water run inside the channel.

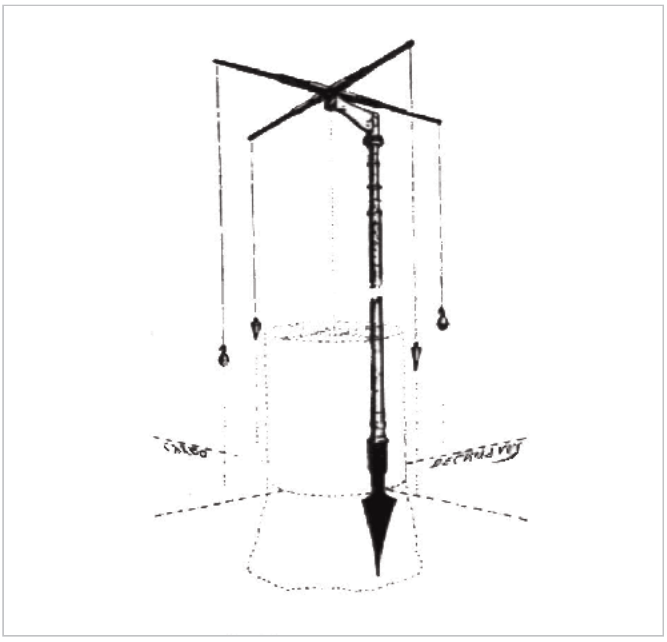

Fig. 5: Groma.
Fig. 5: La groma.

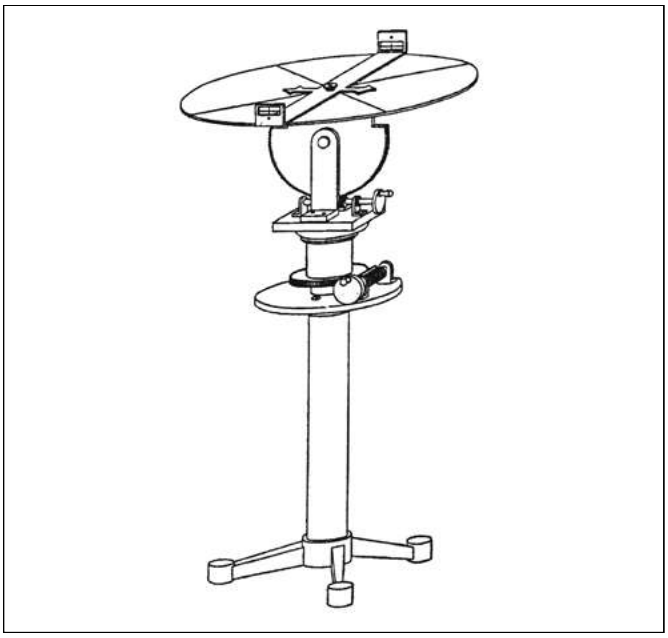

Fig. 6: Dioptra (Wikander, 2000).
Fig. 6: la Diottra (da Wikander, 2000).

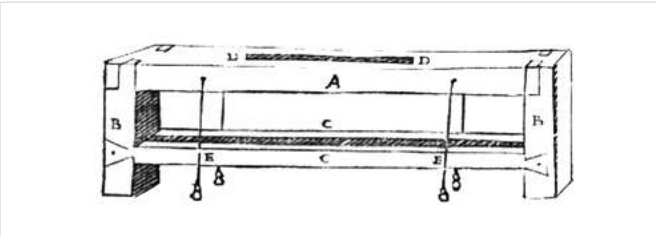

Fig. 7: Corobate.
Fig. 7: il Corobate.

Eight of the eleven Roman aqueducts reached the city at Porta Maggiore (Fig. 8). In the eighties an excellent survey was performed, to measure all the arrival elevations of the aqueducts, on top of the door or transversely (Table 3). The elevations of the Anio Vetus (altitude 43 m a.s.l.?) and Appius (altitude 17 m a.s.l.?) are absent in the table, because they have underground routes that have not yet been identified.

Anio Novus	65,99 m a.s.l.
Claudius	63,85 m a.s.l.
Julia	59,37 m a.s.l.
Tepula	57,61 m a.s.l.
Marcius	55,70 m a.s.l.
Felice	60,90 m a.s.l.

Tab. 3: altimetric heights of aqueducts at Porta Maggiore (after Tedeschi Grisanti, 1987).
Tab. 3: quote degli acquedotti a Porta Maggiore (da Tedeschi Grisanti, 1987).

In addition to the tables above, it is interesting to observe a diagram (Fig. 9) showing the relationship between the quantity of water available and the demographic trends of the city. With the cutting of aqueducts by Vitige (or because Rome had no longer an efficient system of maintenance), the city remained without water and suffered depopulation, and returned to get water from wells, cisterns (rainwater), the Tiber River and from the residual flow that the Virgin Aqueduct could still bring into town.
Only in the XVI century, with the restoration of the Virgin Aqueduct (1570) and the commissioning of

Fig 8: frontal view from south of aqueducts channels, at Porta Maggiore; lateral view of the gate from west.
Fig 8: vista frontale da sud degli spechi, sulla destra di Porta Maggiore; vista laterale della porta da ovest.

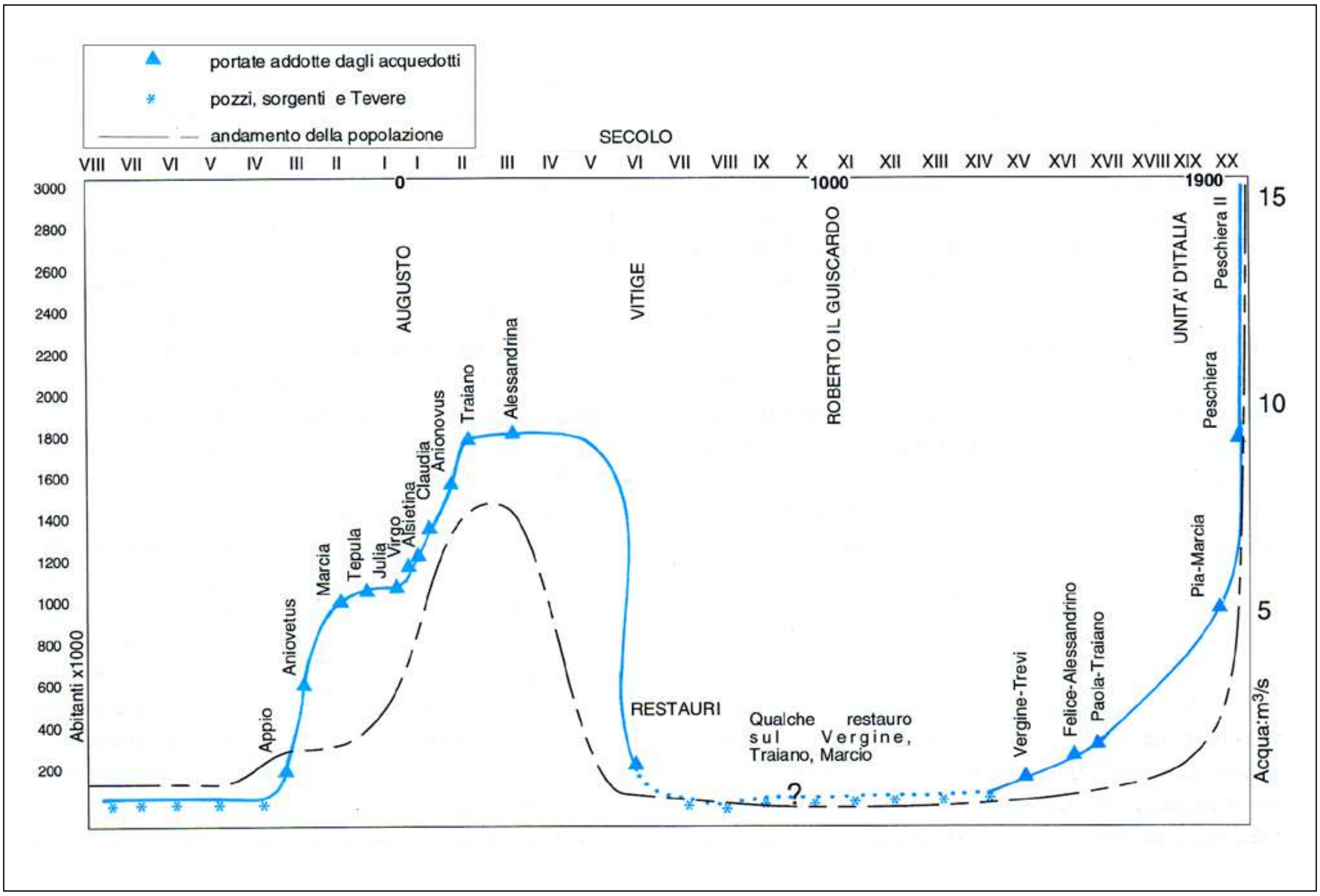

Fig. 9: diagram of Rome demographic change, related to the water flow of the roman aqueducts (L. Lombardi, in Funiciello, 1995).
Fig. 9: diagramma delle variazioni demografiche a Roma in relazione alla portata addotta dagli acquedotti (L. Lombardi, in Funiciello, 1995).

the Felice Aqueduct (1588?), water will return to the city and its hills. In 1600 also the Trajan's Aqueduct was reported in function, which draws water from the Bracciano area. With all these aqueducts, fountains and water features returned to be used, and became the pride of the city.At the end of the XIX century the new Marcius Aqueduct (*Acquedotto Pio antico Marcio*) was reactivated with a technically excellent job. Nowadays the modern aqueduct of Peschiera has finally solved the problem of water supply of Rome and part of Lazio. Everyone knows how the ancient city of Rome was rich in water, with eleven aqueducts that brought to the city a quantity of water that has been reached, and exceeded, only in the 1960s.

The city of Rome had more than one million cubic meters of water per day, with an average consumption of 500 or 1000 liters per person, depending on whether one accepts the estimate of one or two million people in the imperial period. It is known that, although there was this large amount of water, there were few private buildings that were equipped with running water, including the rich *domus*, while most of the population could draw water from public fountains. Over 1,000 baths were also distributed throughout the city, where water was available and plentiful.

In the tables and in the previous sections we have referred to the steep slopes that could cause problems to the structures. To solve these problems, the ancient engineers tried and "invented" specific solutions, which have been studied abroad, but never in Italy, with the exception of a recent study (Pisani Sartorio et al., 2011) on "Trophies of Marius," a large fountain, which ruins are located in Piazza Vittorio, at Rome. In this fountain the water drops over 10 m in height, through a dropshaft, to power a large reservoir that supplied water to a large frontal basin, with jets of water to serve the public. From the same source two large water pipes detached, to supply unknown utilities.

There are three systems used to dissipate the energy caused from sections of tunnels with too high inclinations, where the water flow runs at excessive

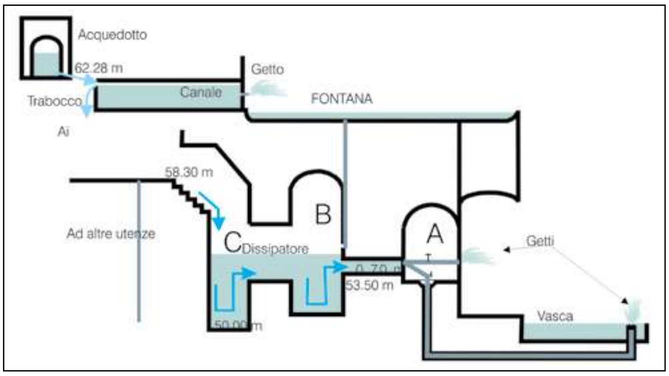

Fig.10: section of the large fountain Trophies of Marius. Presence of a dropshaft - C (after Pisani Sartorio et al., 2011).
Fig.10: sezione della grande fontana mostra detta dei Trofei di Mario. Presenza di un pozzo di dissipazione - ambiente C (da Pisani Sartorio et al., 2011).

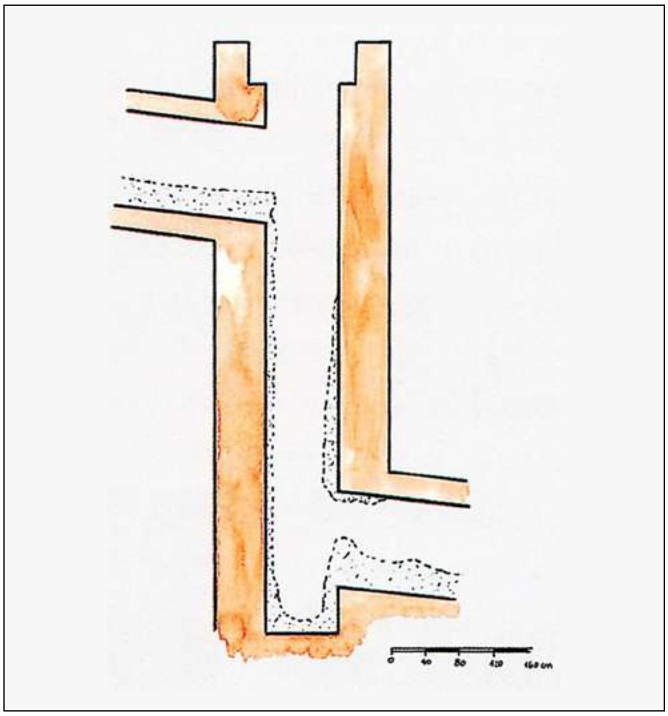

Fig. 11: dissipation well or dropshaft (modified from original drawing by GONZÀLEZ TASCON, VELÀZQUEZ, 2005).
Fig. 11: pozzo di dissipazione (disegno modificato da GONZÀLEZ TASCON, VELÀZQUEZ, 2005).

speed. The first system consisted in creating a dissipation well (dropshafts) 10-15 m deep along the tunnel, in which the water could fell losing energy; at a certain height of the well, a few meters above the bottom, the channel resumed with the normal gradient (Fig. 11). In this way you could decrease the difference in height of about 10 meters. In the aqueduct of Cordoba, Spain, more than ten dropshafts have been discovered, placed in series, with a loss of height of about 100 meters.
Another system, used in many aqueducts in Gaul, was to connect the steep tunnel with a wide gallery (stilling tunnel), where the water lost speed and was fed into

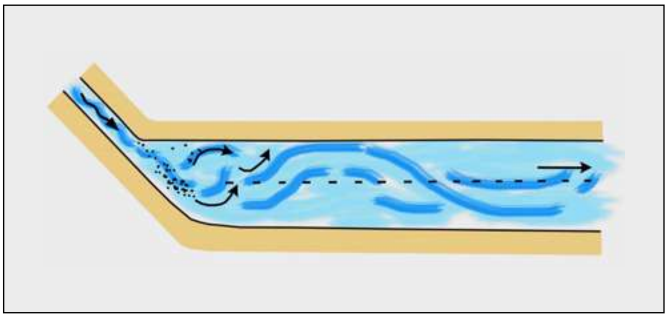

Fig. 12: Stilling tunnel (modified from original drawing by CHANSON, 2000).
Fig. 12: Galleria di calma (disegno modificato da CHANSON, 2000).

a channel at lower height, obtaining a loss of altitude estimated ten meters and beyond (Fig. 12).
A third method was to let the fast water flow, generated by the gallery with a strong inclination, in a large basin (stilling basin), a masonry tank, where water calmed down and lost power finding a larger space, and could be then introduced into the aqueduct conduct. Knowing departure and arrival elevations, we can estimate that the four aqueducts from the Apennines and the two of the Bracciano area had to lose altitude of about fifty meters each.
Long sections with steep slope are present in these hydraulic works, but dissipation systems have never been founded.
In the description of the Roman aqueducts, ASHBY (1991) describes and draws a connection between the four aqueducts from the Apennines (Fig. 13). By opening the valves, it was possible to transfer water from the higher aqueduct, the *Anio Novus*, to those lower in altitude.
In a detail of the previous figure, we can see the dissipation wells (dropshafts) that allowed altitude decrease (Fig. 14).
It is possible, but yet to be demonstrated, that such a system would be used to interrupt the water flow of an aqueduct, when they had to connect a *calix* (Fig. 15) or

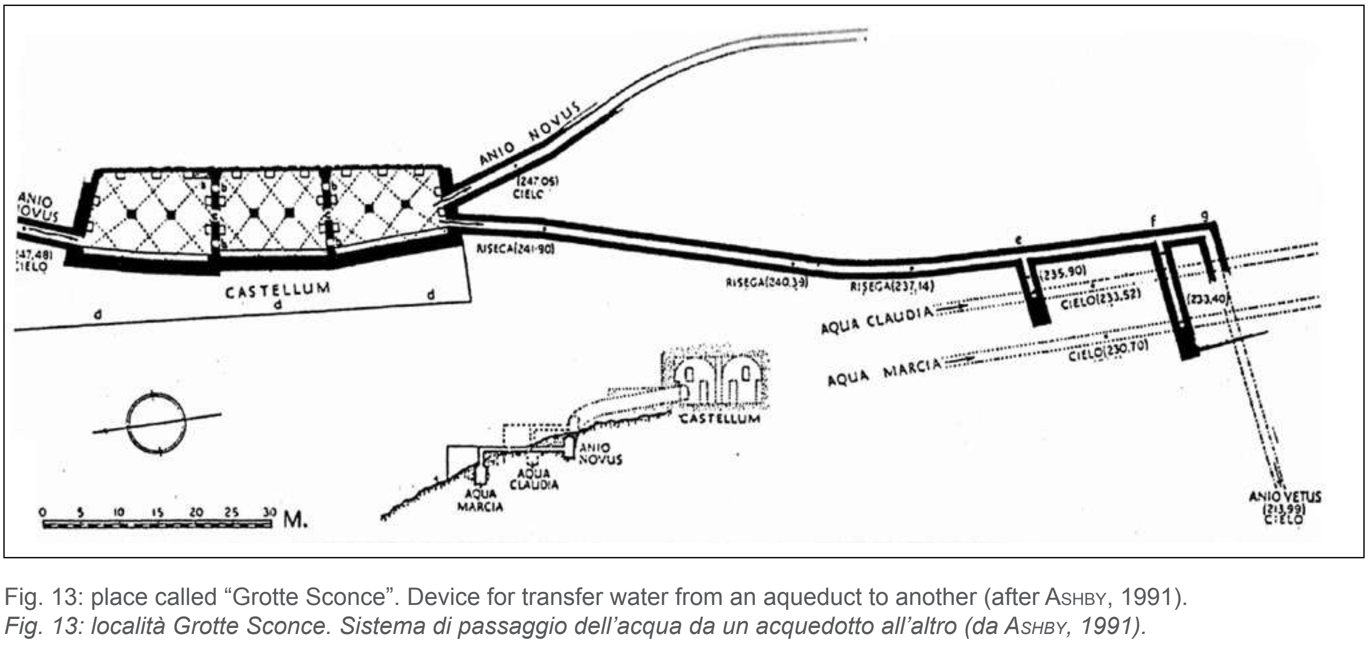

Fig. 13: place called "Grotte Sconce". Device for transfer water from an aqueduct to another (after ASHBY, 1991).
Fig. 13: località Grotte Sconce. Sistema di passaggio dell'acqua da un acquedotto all'altro (da ASHBY, 1991).

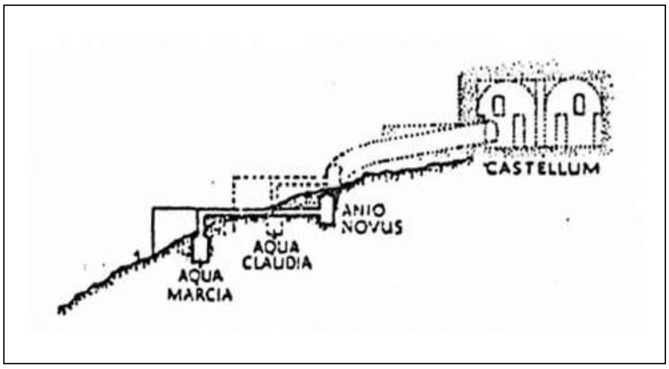

Fig. 14: dropshafts (detail of the previous drawing).
Fig. 14: pozzi di dissipazione (dettaglio del disegno precedente).

Fig. 15: calix (after Ciarallo, De Carolis, 1999).
Fig. 15: calice (da Ciarallo, De Carolis, 1999).

create an opening for water derivations.

Another system, mentioned by Frontinus for the maintenance of aqueducts, allowed to put in place a lead pipe, parallel to the aqueduct conduct, in which divert the water flow; in any case it was essential to interrupt the general flow.

In the Roman countryside, between the Alban Hills and Porta San Sebastiano, there are dozens of farms of the Imperial Age, with baths, heated rooms and pools and, but also with large structures for the production of wine, olive oil and wheat. The large amount of water needed for productive and leisure activities of those villas, was supplied by branches of the aqueducts which pass nearby, along the Appia, Tuscolana and Casilina roads. At least three of these structures can surely be identified. There must have been dozens, and perhaps hundreds, of these structures along the routes of the aqueducts (we know the derivation for Villa Adriana or those for the numerous villas of Tiburtini hills), made with masonry arches or just with piping grafted through a *calix* [1](Fig. 15) in the structure of the aqueduct. Along the aqueducts routes, we can see fragments of walls that lie on the arches, it is possible that these were other diversions, no longer visible today, which reached settlements only partially known. An inventory and study of such structures could extend the knowledge on the water supply techniques, related to the use of the aqueducts.

Reading carefully the texts written by Ashby (1991), we have identified dozens of places where the slopes of the aqueducts are abnormal and exceed, in some cases, 20%. Together with friends of Rome Underground, of which the authors are members, and Egeria, a study work is in progress on these structures, and we start to see the first results. The identification of at least one of these dissipation structure, would bring a major contribution to the knowledge on ancient hydraulic systems, in fact, according to data, six of the eleven aqueducts (Anio Vetus, Marcius, Claudius, Anio Novus, Traianus and Alsietinus) should lose at least 50 m each, to get a proper channel slope. Only in one case we know a system for the loss of altitude, is the case of Aqua Julia, who falls into a large tank and mixes with Aqua Tepula, which has a lower altitude.

1) The *calix* is a bronze tube with a large terminal that was walled up inside the aqueduct's channel. The tube crossed the wall and joined to the lead pipe. Unfortunately, in the current state of research, those elements have not been founded in place. But we know that all the metal components have been looted everywhere and will therefore be very difficult to find some evidences.

References

Ashby T., 1991, *Gli acquedotti dell'antica Roma*, Roma.

Chanson H., 2000, *Hydraulics of Roman Aqueducts: Steep Chutes, Cascades and Dropshafts*. American Journal of Archaeology, vol. 104 (1), Jan. 2000, pp. 47-72.

Ciarallo A., De Carolis E. (eds.), 1999, *Homo Faber. Natura, scienza e tecnica nell'antica Pompei*, Catalogo della mostra, Milano.

Funiciello R., 1995, *La geologia di Roma*, Memorie Descrittive della Carta Geologica d'Italia, Roma, p. 25.

González Tascón I., Velázquez I., 2005, *Ingeniería romana en Hispania. Historia y técnicas constructivas*, Madrid.

Lombardi L., Corazza A., 1995, *Gli impianti tecnici delle Terme di Caracalla*, Roma.

Pisani Sartorio G., Lombardi L., Rossi Zambetti H., 2011, *I 'Trofei di Mario', mostra dell'Aqua Claudia-Anio Novus: il percorso dell'acqua*. Rend. Pont. Acc. Rom. Arch, vol. LXXXIII, Anno Acc. 2010-2011, pp. 59-89.

Tedeschi Grisanti G., 1992, *Primo contributo ad una livellazione urbana sistematica degli antichi acquedotti di Roma*, in Il trionfo dell'acqua, atti del convegno 'Gli antichi acquedotti di Roma: Problemi di conoscenza, conservazione e tutela', Roma.

Wikander Ö., 2000, *Handbook of Ancient Water Technology*, Leiden-Boston-Köln, p. 55.