Water supply of ancient Rome

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Abstract. The paper gives an overview about different parts of the water supply of the ancient Rome. An important component are the famous aqueducts like the Aqua Marcia, the Aqua Anio Novus and the Aqua Claudia. Aque ductus in latin means water pipe in English. Archaeologists use the word aqueduct as an above ground laying part of the water pipe, which can reach several storey. (www.projekt-wasserversorgung.de) Water pipes consisting of lead, clay or/and opus caementium formed the basis of the water supply system. Baths and fountains were available for the public pleasure and regeneration. And the Roman sewage system was one of the first worldwide.

Introduction

The rural town of Rome of the 7th till 3rd Century BC covers the water demand from the river Tiber and other sources without any problems. With increasing population and living standard the water supply became worse. (www.geocities.com)
Rome is situated in a warm climate zone and the quality of the water of the Tiber became undrinkable with increasing temperature. (www.projekt-wasserversorgung.de)
So they decided in 312 BC, when the town had several thousand inhabitants, to contract the first aqueduct: the Aqua Appia. But not at least the safe water supply and the efficient sewage system were the reasons for the rapid growth of the city. It expands over the neighbored hills, which are laying above the plain between the city and the water-rich highland in the east. The water pipes that were usually run at the ground couldn’t reach the hills. The ten aqueducts, which followed, considered that. All water pipes (aqueduct) were open channels driven by gravity flow. That means the water didn’t flow in sealed tubes but in rectangular channels with
“free” water level, which required a persistent gradient. The pipes ended in distribution buildings (castelli) or in magnificent fountains (naumachiae). At the castelli branches of the pipes begun and continued into the several parts of the city (regiones), the fountains, the baths, the house connections and the business establishments. Surplus of water flushed the sewage system. These pipes named fistulae were made of clay or lead and 10 standard sizes of them have been existed. (www.geocities.com)

The greatest water demand has to be assumed for the spa’s, pools and baths. In the 4th century Rome had 11 larger and 850 smaller pools and baths, which could only existed because of the generous water supply. The inhabitants of Rome had 150 public holidays so they used them to stay there whole days. They could take a bath in different tempered basins, went there to lunch with business friends, worked out or got a massage. To visit a bath was a social event. The Baths of Caracalla had 11.000 servants, which could care for 3.000 visitors at the same time. (www.geocities.com)

Overall the water was used to 44 % for public constructions (fountains, fountain houses, basins, cistern), 38 % for private demand in the houses and 19 % for the imperial court. (www.projekt-wasserversorgung.de)

Main Part

Aqueducts

Specific problems at the line planning of the water pipes made the leveling because optic instruments were unknown. They built with very low gradient for example at the Aqua Anio Novus: 1,3 per mill (1,30 m on 1 km). To make those precisely measurements on unknown terrain matured measuring technique and reliable devices are needed. The Roman Architect Vitruv (the author of a famous 10 volumes comprehensive opus about the architecture and technique of his time in the 1st century BC) described such an instrument: the Chorobat (see Fig. 1). That is an instrument for leveling that is in function and appearance similar to a spirit level. A 6 m long bar provide with horizon and corn and in the middle of it there was a narrow gutter. If one fills the gutter with water until the upper edge was reached, the two target marks formed an exact horizontal line. Now you elongate the distance by focusing on 30 m and fixed that at stakes with two boards. If one puts a bar, with a height of 0,03 m; on one of the boards the upper edges formed a gradient of 1 per mill that means 1 m on 1 km. With a leveling board one can measure the altitude of the ground. Step by step one gets a consistent line. Mostly the Romans fixed points far away and afterwards they calibrate the points between these distances during the construction. (www.geocities.com)
All aqueducts were mentioned in the following table 1 with their sources, length and the construction time. After that table some of them will be described in detail.

Table 1. An overview of all 11 aqueducts
(modified after www.projekt-wasserversorgung.de)

<table>
<thead>
<tr>
<th>Title</th>
<th>Time of construction</th>
<th>Length in km</th>
<th>Area of sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appia</td>
<td>312 BC</td>
<td>16,6</td>
<td>Springs in the Anio-valley</td>
</tr>
<tr>
<td>Anio Vetus</td>
<td>272 BC</td>
<td>64,0</td>
<td>River Anio</td>
</tr>
<tr>
<td>Marcia</td>
<td>144-140 BC</td>
<td>91,2</td>
<td>Springs in the Anio-valley</td>
</tr>
<tr>
<td>Tepula</td>
<td>125 BC</td>
<td>18,4</td>
<td>Volcanic springs in the Albanian Mountains</td>
</tr>
<tr>
<td>Iulia</td>
<td>33 BC</td>
<td>22,8</td>
<td>Springs in the Albanian Mountains</td>
</tr>
<tr>
<td>Virgo</td>
<td>21-19 BC</td>
<td>20,8</td>
<td>Springs in the Anio-valley</td>
</tr>
<tr>
<td>Alsetina</td>
<td>10-2 BC</td>
<td>32,8</td>
<td>Lacus Alstetinus (Lake Martignano)</td>
</tr>
<tr>
<td>Claudia</td>
<td>38-52 AD</td>
<td>68,8</td>
<td>Springs nearby the springs of the aqua Marcia</td>
</tr>
<tr>
<td>Anio Novus</td>
<td>38-52 AD</td>
<td>86,4</td>
<td>River Anio above Subiaco</td>
</tr>
<tr>
<td>Traiana</td>
<td>109-117 AD</td>
<td>59,2</td>
<td>Springs nearby lake Bracciano</td>
</tr>
<tr>
<td>Alexandria</td>
<td>226 AD</td>
<td>22,4</td>
<td>Springs at Sasso Bello</td>
</tr>
</tbody>
</table>
Aqua Appia

The first aqueduct was built in 312 BC. The realization of the project was paid from public funds. In 144 BC the aqueduct was leaking because of its age and of unlawfully puncturing by private people. The aqua Appia was repaired again in 33 BC. (Kleijn 2001)

Six years later, the aqueduct has got a new branch named *ramus augustae*. The spot where the two supply channels were united was called *gemelli* (≡ twin). The total length of the original aqua Appia amounted 16,56 km. 0,09 km of them were above ground on substructures and arches. The major part ran under ground because Appius Claudius had frightened military attacks by the enemies of Rome. (Kleijn 2001)

The *ramus augustae* ran completely underground. In the aqueduct was no settling tank incorporated. Because of the low level (the beginning of the aqua Appia was approx. 14,8 m above the surface of the earth) at which the water pipe entered the city the possibilities for distribution of the Appia’s water were rather limited. On the other hand the channels were less vulnerable to injuries from outside. (Kleijn 2001)

Indeed in the city leaks and prohibited punctures reduced the total amount of water. With the aid of a bridge water was conveyed from the aqua Appia to the other side of the Tiber. (Kleijn 2001)

Aqua Anio Vetus

In 272 BC, 40 years after the Aqua Appia was built, a 2nd aqueduct was planned. (Kleijn 2001)

After a few years the building was finished. It brought surface water, sometimes of poor quality, from the river Anio to the city and was therefore named *aqua Anio*. In the 1st century AD when a second aqueduct was built, which drew its water from the same river, the name of the former was extended with the adjective *vetus* (≡ old) to differentiate the second aqueduct from the latter. The Aqua Appia and the Anio Vetus were repaired several times. They bear traces of 3rd century repairs. The length of the Aqua Anio Vetus averages 63,64 km, of which 0,33 km ran above ground. It was so long because its route followed the slopes of the hills as much as possible and only sometime crossed a valley, with the effect that height was lost. The beginning of aqueduct was situated above Tibur (Tivoli) and the intake not only served the aqua Anio Vetus but also an aqueduct for Tibur (a city near the river Anio). There had been existed a conjunction between the aqua Marcia, which will be built later, and the aqua Anio. It was described by Frontinus (Sextus Iulius Frontinus who was appointed to *curator aquarum* of the city of Rome in 97 AD wrote a booklet about the water in Rome named “De Aquis Urbis Romae”) and confirmed by archaeological evidence. The Anio Vetus had its own settling tank (*piscina*). Like the aqua Appia, the aqua Anio Vetus did not have enough height to supply the entire city with water. (Kleijn 2001)
**Aqua Marcia**

In 144 BC, according to Frontinus, the senate considered to repair the two existent aqueducts leaking from old age, and to reclaim the water illicitly diverted by private people. The new aqueduct was entitled after the constructor Marcia. In 146-145 BC three victorious armies had returned to Italy and many veterans wanted to try their luck in Rome so the population increased suddenly. Where the money came from can be speculated only. The praetor for legal practice between Roman citizen quintus marcius rex was appointed to eliminate the leaking and the illicit water diversion and to enlarge the water quantity of the city. Either he had to supplement the existent two aqueducts with new sources or to construct a new water pipe. He decided to realize the latter. In fact Marcius obtained 180 million sesterzen for his three assignments. The aqua Marcia had a length of approx. 91,33 km of which approx. 80,28 km were ran underground and approx. 11,05 km above ground. The sources have been found in an elevated valley of the river Anio and the route of the water pipe is rather well known. From the settling tank the aqueduct continued above ground on arches 9,58 km and 0,78 km on substructures. After this stretch the water pipe disappeared from sight again. If the aqua Marcia ran dry, water was ordered to be adding from another spring, a little further on in the Anio-valley than the first, by means of an underground channel into Marcia’s original water pipe. (Kleijn 2001)

Under normal conditions the aqua Marcia was not in need of such a supplement and therefore, at some point in the 1st century AD Marcia’s surplus was conducted into the aqua Claudia. This name is based on the reign of Claudius. Somewhere between the sources and the settling tank, apart of the water of the aqua Marcia was given to the Anio Vetus and the aqua Tepula. In 33 BC the aqua Iulia was constructed and the aqua Tepula was transformed on top of the aqua Marcia. Archaeological evidence indicates a branch from one reservoir to another behind of the Baths of Caracalla. It’s plausible that the aqua Marcia supplied his baths and the Baths of Diocletian, which could be proved by a stretch to a reservoir of these baths. (Kleijn 2001)

**Aqua Tepula**

In 125 BC, the aqua Tepula was built on top of the aqua Marcia. The water that had been delivered was tepid and therefore unappreciated. Measurements showed a water temperature of 16-17 °C at an air temperature of 10 °C. There are no known remains of the aqueduct as a separate construction. In 33 BC the tepid water was mixed with the fresh supply of a new aqueduct, the aqua Iulia, drawing its water from sources nearby those of the Tepula. The beginning of the Tepula was the settling tank of the aqua Iulia. From there the Tepula had its own channel between those of the aqua Marcia and Iulia. It received water from the aqua Marcia just beyond the settling tank. The channel of the Tepula had enough height to distribute water all over the city. The aqueduct was repaired between 11 and 4 BC and some later repairs have been attested by archaeological evidence. (Kleijn 2001)
**Aqua Iulia**

Agrippa, Augustus son-in-law, the appointed man for Rome’s water supply in 33 BC repaired the existent aqueducts, the aqua Appia, Anio and Marcia, rebuilt the aqua Tepula and constructed a new one the aqua Iulia. Their sources were situated 3,4 km from those of the Tepula. Probably he financed it of his own fortune. The aqua Tepula was intercepted and its water was mixed with that of the new water pipe Iulia, as a single channel. The water of both aqueducts arrived at the settling tank. At this point the water was separated: a minor part continued on as aqua Tepula und the reminder continued as aqua Iulia, the highest of three channels on the substructures and arches originally built for the aqua Marcia. The aqua Iulia has a length of approx. 22,83 km. 10,39 km ran above ground in common with the aqua Marcia and Tepula. Like these two aqueducts the Iulia had enough height to be distributed all over the city. (Kleijn 2001)

**Aqua Claudia**

When Emperor Caligula had reigned, the existent seven aqueducts scarcely sufficed to meet the requirements of public use and private pleasure and so he decided to build two new water pipes. Indeed he did not live long enough to see their completion. In 52 AD it had been finished under Claudius, who built at his own expense. The aqua Claudia draws its water from two copious springs. The total length of the aqueduct averages approx. 68,68 km of which approx. 53,62 km ran underground and approx. 15,06 km above ground. Over a length of 10 km beyond Rome it has been ran above ground at the famous queue of arcades. At the upper course the gutter ran on arches (approx. 4,55 km) and near the city on substructures approx. 0,9 km and on arches approx. 9,61 km. The sources of the aqua Claudia and the Marcia were situated not far away from each other but the channel of aqua Claudia was some 22,65 km shorter than the channel of the aqua Marcia, because of the more ample use of bridges in the upper course. (Kleijn 2001)

Depending on requirement various springs were transmitted to the aqua Claudia and Marcia like the Augusta-spring. (Frontinus 1989)

The aqua Claudia and the aqua Anio Vetus had the same settling tank. Both channels met each other and went together as one. The aqua Anio Novus ran on top of these combined aqueducts. The end of both water pipes had enough height to distribute the water all over the city. (Kleijn 2001)

**Aqua Anio Novus**

The aqua Anio Novus was built by Claudius and draw surface water from the river Anio. A little further on, the surface water was combined with water from a spring. It got the adjective novus (= new) to prevent confusion with the earlier aqueduct, which got the adjective vetus (= old). (Kleijn 2001)

The total length of the aqueduct averages approx. 86,87 km of which approx. 72,96 km ran underground and 13,91 km above ground. Most of the substructures
and arches were located near the city, where the aqua Anio Novus ran on top of the aqua Claudia. (Kleijn 2001)

Van Demain recorded original diversions from the main channel of the aqua Anio Novus into the lower aqua Marcia, Claudia and Anio Vetus. Originally the water was conveyed from a river that ran through arable land and had loose banks so its water was always muddy and turbid. The settling tank sufficed in fine weather but fell short after showers so it polluted the other aqueducts. As a consequence they had been reconstructed the intake at a different place. It was the highest aqueduct of all and so the water was distributed all over the city of Rome. (Kleijn 2001)

The water pipes

The people took their water mostly from fountains. To get the water directly into the house they must met some conditions like the dimension and length of the pipes which lead from the private houses to the distribution basins. First with fulfillment of these conditions they got an access with a certified stamp. These standardized sizes of the pipe diameter (calices) allowed an accurate measurement and payment of the daily water demand that were equivalent to approx. 420 l/house. (www.projekt-wasserversorgung.de)

Only rich inhabitants were able to afford the house connections because they were associated with costs. (www.geocities.com)

It wasn’t possible for the inhabitants of houses with several stories to get their water from the water pipes therefore they had to use the public fountains. (www.projekt-wasserversorgung.de)

In spite of the calices cheating was very usually. The masters of water made their own business with illegal puncturing. They changed the calices against greater ones or sold the overflow water, which should actually flush the sewage system. (www.geocities.com)

Like today the water pipes, aqueducts and distribution basins had to be inspected, repaired and illegal punctures to be removed. The approx. 60 km of bridges and aqueducts were especially vulnerable to repair. In addition they must clean the castelli. Around the year 100 AD the water works had approx. 700 employee workman and pipe runners. According to the water quantity it is a ratio like today of one person per million-m³ water. (www.geocities.com)

Lead pipes

The diameter of the lead pipes used ranged between 25 and 300 mm. Nearly all pipes, consisting of rectangular lead plates, were formed around a cylindrical shape and were soldered on the longitudinal and vertical borders of the pipe. Therefore the cross-section was pear-shaped not circular. Tests for breaking strength have shown that Roman lead pipes with a wall thickness of 7 mm at an overpressure of 3 bars get wider. At an overpressure of 8 bars the circular shape is
reached, at 18 bars fissures appear. Damages were repaired with muffs, which shuffled above these spots and were soldered with the pipe. (Frontinus 1989)

The pipes were composed of nearly 99 % lead. It is unexplained where the high lead content is coming from. In nature you can’t find it and by smelting it is relative implausibly due to the technique applied. (Frontinus 1989)

The question is whether the noxious qualities of lead were generally known and whether, as a consequence, other materials than lead were chosen for water conduits. Almost all of the lead absorbed by the human body is deposited in the bones. The investigation of ancient bone material is essential in order to verify whether the Romans were victims of lead poisoning. Investigations of human bones analyzed on lead at the town Herculaneum, the great “brother” of Pompeii, show a “relatively low accumulation of lead in most of the skeletons” (after Hanson 1989). Herculaneum by the way was destroyed during the same serious of eruptions that had destructed Pompeii. (Bruun 1991)

It is undeniably that elsewhere the lead content in bones from Roman times was considerably higher than in some modern great American cities (after Fornaciari & Mallegni 1989). There are three sources for lead in Rome, which are assumed for the high lead content in the bones. On the one hand the water supply with a net of lead water pipes and on the other hand the Romans added to their wine a lead-containing additive called sapa (“zucchero di piombo”= the sugar with lead). The 3rd reason was the cooking vessels of the Romans, often made of a compound of lead and tin. But because of two other facts it seemed that a high lead content in bones does not necessarily mean that water pipes of lead had been used. It could also be the cooking vessels and the wine. Hodge (1981) pointed out that the lead pipes would not have contaminated the water because the Roman water contained large amounts of calcium and near neutral pH, which formed deposits (sinter) inside the pipes, insulating the lead. Another fact is lead will never greatly affect continuously flowing water (after Hodge 1981). (Bruun 1991)

Fornaciari & Mallegni (1989) concluded that the accumulation of lead in bone tissue, although higher than normal, would have been so gradual that no significant clinical effects would have been discernable. There are known few literary sources, which testify that lead was regarded as unhealthy. In spite of this knowledge people take pride in the installation of fistulae (lead) that is proved by a number of inscriptions. (Bruun 1991)

**Clay pipes**

In general the Roman clay pipes have different forms and different wall thickness. (Frontinus 1989)

The length averages between 30 and 60 cm, but there also occurred pipes of 80 cm length. Fine-grained clay, a smooth outer surface and profiles at the ends of the pipes were the distinguished marks of the Roman clay pipes. They were formed nearby cylindrical. Vitruv said: “if somebody want to construct a new cheap water pipe...so you must produce clay pipes with thick walls and with at least two inches diameter in such way that they reducing their diameter to one an in order
that it can be plugged into one another. The seam must be elapsed with fresh slaked lime which is mixed with oil…the advantages of a pipe consisting of clay is that the destroyed parts can be repaired from an unskilled worker and it is supposed that they are more healthful than lead pipes.” (Frontinus 1989)

**Opus caementium = Roman concrete**

The first aqueducts were made of brickwork but the younger ones of opus caementium (= Roman concrete). It consists of limestone (adhesive cement) with or without clay. It is fired by 1000 °C and eventually mixed with pozzolan. Pozzolan is a silica or silica-clay mixture, which often contain material with volcanic origin. The Roman concrete were inserted in layers between a lost casing consisting of stone walled stones or wooden boards. (www.beton-info.org)

In contrast to this modern concrete is a mixture of limestone and clay. After powdering it is fired by 1400 °C and eventually mixed with sand or similar material. It has high compression strength and can harden under water. In addition it is water resistant. (www.beton-info.org)

To make the channels waterproof and resistant to environmental influences they had to be coated with multi-layer finery. It should be avoid tension fissures caused of climate changes and other stress. The successful solutions of the Romans for the material of channels attest a very good understanding of these influence factors. (Frontinus 1989)

The secret of the multi-layer finery was the high density and stability of some of these layers, which were achieved by abrasion and polishing of the single layers. At the same time the components lime and marble were crushed to powder. Whereby the specific surface could be increased and the formation of capillaries was reduced. At the end the multi-layer composition of the finery guaranteed a high density and stability, low water absorption, insignificant strains at the moistening and dehydration as well as extra ordinary resistance. Therefore the finery was widely free of cracks and waterproof. (Frontinus 1989)

**Sewage system and Roman toilets**

Already in the 4th century the *cloaca maxima* was developed to lead the ground- and wastewater into the Tiber, who flushed it into the ocean. During the next centuries this first drain was expanded to a whole channel network. The gullies and toilets were connected to this system. (www.projekt-wasserversorgung.de)

The water of the unstoppable fountains also ran into the sewage system and guaranteed a good flushing. This was necessary because beside the wastewater also solid waste must be transported into the Tiber and this caused environmental problems because wastewater was mixed with drinking water. (www.geocities.com)

Public latrines have existed everywhere at the settlements. They were mass toilets, seat on seat and a source of gossip. Sometimes they were even heated. In Dougga/ Tunisia 12 seats consisting of limestone were arranged in one toilet room: origi-
nally the floor showed a mosaic and around the mosaic was a half-round gutter without any drainage. Inside of this gutter water stood for cleaning. The feature of the Roman toilet was the new system of canalization channels, which transported the excrements away and held the bad smell at a low level. Roman private houses were equipped with both chamber pots and permanent abort chairs where excrements fell down in a cavity or sewage canal. Also covered aborts were common in private houses. (Frontinus 1989)

Conclusion

It is a fact that ancient Rome had been so positive developed as a result of the fortunately water supply. Thus they reached a high living standard for those times. House connections (piped water) made the live more comfortable, baths and fountains, which were mostly for pleasure and the sewage system, which reduced the bad smell and preserve the hygiene, characterized this. By the use of 11 aqueducts, which draw the water from kilometers far away sources, they were no longer dependant from surface water and springs. So they could minimize the diseases that were water-borne. The water technique and the sophisticated skills of the Romans were unbeatable for 1,500 years. First in the 20th century this standard of water supply was reached again.

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