Some elements of the water supply system of the city of Perge, in the Roman Imperial period

F. Debaste¹, B. Haut²

¹ TIPs, Université Libre de Bruxelles, Av. F.D. Roosevelt, 50, C.P. 165/67, 1050 Brussels, Belgium
² TIPs, Université Libre de Bruxelles, Av. F.D. Roosevelt, 50, C.P. 165/67, 1050 Brussels, Belgium (Corresponding Author) (E-mail : bhaut@ulb.ac.be)

Abstract In this paper, an overview of some elements of the water supply system operated in Perge during the Roman Imperial period is presented. The focus is given on a channel in the middle of the main colonnaded street, presenting a complex structure with obstacles every 7 meters. On the basis of an analysis of the flow of water in this channel, an interpretation of the motive of the presence of these obstacles is proposed. It is thought that they had the primary function to significantly increase the maximum water height in the channel (76 cm with the obstacles, 10 cm without). A high water level in the channel is indeed needed for the operation of derivations starting from the channel. Moreover, the calculated structure of the flow created by these obstacles highlights the cleverness of the Roman engineers, as well as the importance of water to satisfy the pleasure of the people.

The south bath complex of the city is also briefly presented.

Keywords: hydraulics, masonry channel, bath complex, water flow rate
INTRODUCTION

The archaeological site of Perge is located 11km from the Mediterranean coast, in Turkey (see Figure 1). The site has been occupied since the 3rd millennium BC. After the arrival of Alexander the Great in 334 BC, it passed under the control of various Hellenistic kingdoms, and under Roman’s rule in 188 BC. Later on, Perge gained a genuine prosperity in the 2nd and 3rd centuries AD, during the Roman Imperial period. Most of what can be seen today at the site comes from these centuries, such as the theatre, the stadium, the agora and the baths. There was a last period of prosperity during the 5th and 6th centuries AD. The city walls were extended southwards and the city was decorated with many churches (Abbasoglu 2010, Tunçer 1992).

In the 8th century AD, the raids by mountain tribes and the Arabs, coupled with the development of Antalya, led Perge to decline. Perge was finally ruined during the Seljuk and Arab raids in the 12th century AD and was deserted by the people (Tunçer 1992).

The Romans used water for the irrigation of cultivated fields and for urban needs. In the cities, fountains were flourishing; large baths and latrines were present. This led to a high need for water; daily consumptions between 200 and 500 l per capita are reported (Bailhache 1979, Hodge 2008, Kessener and Piras 2008). According to Vitruvius, water not only satisfies the needs of the people, but also their pleasure (Morgan 1960).

It is commonly admitted that the Romans had a remarkable engineering knowledge of water supply (Haut and Viviers 2007, Hodge 2008, Ortloff 2009, Viollet 2004). Water was carried to the Roman cities through aqueducts that could reach more than 100 km long. Within the cities, water was distributed through a complex combination of water towers and pipelines. Wastewater was evacuated from the cities by drainage systems. Only a few Roman writings on this engineering practice have been preserved. However, archaeology offers some precise illustration of their techniques (Haut and Viviers 2012). The surviving written records of Frontinus (Evans 1994, Herschel 1973) and Vitruvius (Morgan 1960) provide some understanding of water supply systems in the Roman period. While these works give insight into the design methodology of water supply systems of that period, they reflect pre-scientific views of hydraulic principles (Ortloff 2009). For instance, in the work of Frontinus, such a concept as the flow rate is not known.
Numerous astonishing hydraulic remains from the Roman Imperial period are observed in Perge. Due to the importance of the city in this period, these remains provide an excellent picture of the best available technology at that time. For instance, a monumental fountain, at the bottom of the acropolis, delivered water in a canal at the centre of the main colonnaded street (Figure 2). A monumental bath complex is one of the best preserved buildings in Perge. It is located south of the main street (Figure 2). In the Agora, located at the southern end of the colonnaded street, the remains of latrines, a cistern and a fountain can also be observed.

Figure 2 Simplified map of the actual remains of the city of Perge.

In this paper, some elements of the water supply system of the city of Perge, in the Roman Imperial Period, are presented and analysed. The focus is given on the channel in the middle of the main colonnaded street. The south bath complex of the city is also briefly presented.

CHANNEL IN THE MIDDLE OF THE MAIN COLONNADED STREET
A masonry channel with an open surface flow is observed in the middle of the main colonnaded street (Figure 3). No sign of covering blocks are attested. The start of several derivations composed by terracotta pipes is observed along the channel (Figure 4). Water was delivered into this channel by a monumental fountain located at the south of the acropolis, at the north end of the main street (Figure 2). In this fountain, water coming from the top of the acropolis was delivered to a large decorative pool through an opening just below a reclining statue (Figure 5). From this pool, water overflowed into the channel built in the middle of the colonnaded street. Approximately every 7 m in the channel, stone cut obstacles are observed.
Their role is discussed later in this paper. This spectacular water system was constructed during the 2nd or the 3rd century AD (Abbasoglu 2010, Tunçer 1992).

Figure 3 (a) Masonry channel with an open surface flow in the middle of Perge main street and with obstacles every 7 m. (b) Schematic top view of this channel, with the altitudes of some points.

Figure 4 Derivation starting from the channel at the centre of Perge’s main street.
The maximum flow rate of water that could be transported by this system can be approximately calculated. A schematic lateral view of the overflow of the water from the pool to the channel is proposed in Figure 6. The staircase structure on this representation, with six 14 cm high steps, can be observed in Figure 5.

**Figure 5** Monumental fountain at the south of the acropolis of Perge and at the north of the main street. Water overflowed from the pool of this fountain to the channel in the middle of the main street.

**Figure 6** Lateral view of the overflow of water from the pool to the channel.
The largest possible value of $h$, the height of water above the staircase structure (see Figure 6), is 16 cm. Indeed, if $h$ was larger than 16 cm, the water would have flown over the lateral walls of the pool; but no calcareous concretions are observed on these walls. It can be assumed that the flow on the top of the staircase structure was critical, i.e. characterized by a Froude number (Fr) equal to unity (Lencastre 1995):

$$Fr = \frac{v}{\sqrt{gh}} = 1$$

where $v$ is the velocity of the water on the top of the staircase (see Figure 6).

Therefore, $Q$, the maximum volumetric flow rate of water in the channel, can be calculated as follows:

$$Q = hLv = L\sqrt{gh}^3$$

where $L$ (= 1.8 m) is the width of the cross section of the flow on the top of the staircase structure and $g$ is the acceleration of gravity. $Q = 31000$ m$^3$/day is calculated.

The inner width of the channel is equal to 2.4 m. This large value, compared to usual values of channel inner width in Roman engineering, might have been chosen for aesthetic reasons, as the channel is in the middle of the main street. The channel has average slope of 1.8 cm/m between points 1 and 3 in Figure 3. As the obstacles in the channel are separated by 7 m, the height difference between two successive obstacles is 13 cm (between points 1 and 3 in Figure 3).

The Manning equation can be used to calculate the maximum height of water that would have been observed in the channel if there were no obstacles in it. This equation writes as:

$$Q = \left(\frac{bH}{b+2H}\right)^2 \frac{2g\theta}{29n^2}$$

where $Q$ is the maximum volumetric flow rate of water in the channel, $\theta$ the channel slope, $g$ is the acceleration of gravity, $b$ the channel inner width, $H$ the maximum water height in the channel if there were no obstacles, and $n$ a friction coefficient. For a calcareous deposit in a masonry channel, $n$ is close to 0.014 m$^{1/6}$ (Lencastre 1995).

Using a friction coefficient $n = 0.014$ m$^{1/6}$, a channel slope $\theta = 1.8$ cm/m, a channel inner width $b = 2.4$ m and a maximum volumetric flow rate $Q = 31000$ m$^3$/day, a value of $H = 10$ cm is obtained. This small value of the maximum water height that would be obtained in the channel if there were no obstacles is obviously a consequence of the large width of the channel. Such a small value of the water height in the channel would have led to a small pressure at the beginning of the derivations starting from the channel, and hence to difficulties to operate such derivations.

The flow in the channel was of course considerably influenced by the presence of the obstacles. It can be assumed that the flow of the water over the obstacles in the channel was critical, i.e. characterized by a Froude number equal to 1. Therefore, it can easily be demonstrated that the maximum height of water above the obstacles, $h_o$, can be calculated with the following equation:
\[ h_o = \left( \frac{Q}{b} \right)^{\frac{2}{3}} g^{-\frac{1}{3}} \]

\( h_o = 13 \) cm is calculated. The height difference between the top of the obstacles and the top of the lateral walls of the channel is 15 cm. Consequently, a schematic representation of the flow in the channel is proposed in Figure 7.

The motive of the presence of these obstacles in the channel is of course questionable. Based on the proposed analysis, it can be thought that they had the function to significantly increase the maximum water height in the channel (76 cm with the obstacles, 10 cm without). A high water level in the channel is needed for the operation of the derivations starting from the channel. Furthermore, this “cascade” structure of the flow created by these obstacles should have looked quite aesthetic in the middle of the main street of the city. One may here recall Vitruvius, stating that “water not only satisfies the needs of the people, but also their pleasure”.

Figure 7 Schematic representation of the water flow in the channel at the centre of Perge main street.

BATH COMPLEX AT THE SOUTH OF THE MAIN STREET

Baths were of extreme importance in Roman times. They were the place to meet friends, but also the place to find facilities that most of the people did not have at home. Therefore, they also played an important role in public health (Hodge 2008).

The baths needed a large amount of water for the operation of their heating systems and to fill their numerous pools. They were probably the main reason for the construction of the aqueducts (Hodge 2008).

The monumental bath complex is one of the best preserved buildings in Perge. It is located south of the main street (see Figure 2). These remains illustrate the classical Roman Imperial structure of baths, with a symmetrical organization of the different rooms of the building. Their size demonstrates their importance in Roman times.
The dressing room, the cold baths (frigidarium), the warm baths (tepidarium) and the hot baths (caldarium) were classically lined side by side, offering therefore to the users the flexibility to go from one room to the other. The heating system (hypocaust) of the hot and warm baths can still be observed today (Figures 8 and 9). These south baths were characterized by several phases of (re)construction from the 1st century AD to the 5th century (Abbasoglu 2010, Tunçer 1992).
CONCLUSIONS
In this paper, an overview of some elements of the water supply system operated in Perge during the Roman Imperial period is presented.

The south bath complex of the city is briefly presented, but the focus is given on the channel in the middle of the main colonnaded street, presenting a complex structure with obstacles every 7 meters. On the basis of an analysis of the flow of water in this channel, an interpretation of the motive of the presence of these obstacles is proposed. It is thought that they had the primary function to significantly increase the maximum water height in the channel (76 cm with the obstacles, 10 cm without). A high water level in the channel is indeed needed for the operation of derivations starting from the channel.

Only a few Roman writings on water engineering practice have been preserved. However, the remains analysed in this paper give a picture of the best available water technology in the Roman Empire, especially between the 2nd and the 4th century AD. The analysis of the operation of the channel inside the city limits, including use of actual knowledge in fluid mechanics, highlights the cleverness of the Roman hydraulic engineers (see the numbers on Figure 7), the large extent of hydraulics work in Roman times, and the importance given to aesthetics in Roman water engineering.
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