Water History (2023) 15:363–392
https://doi.org/10.1007/s12685-023-00333-2

Water quantities for public and private use in Pompeii

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Received: 11 April 2022 / Accepted: 1 November 2023 / Published online: 26 February 2024

Abstract
The water-supply system in Pompeii delivered water to both public and private water users. Aqueduct water was distributed in three main water pipelines. The aqueduct water was led up to fill lead containers on top of a number of water towers, and from there it continued downhill from one tower to the next located at a lower level. All top containers also had connections to small individual lead water pipes to public and private users in the different districts of the city. However, it still remains unclear how and with what efficiency aqueduct water could reach all users, some of them at a far distance from the water towers, in a system based on gravity flow. In this study the focus is to explain the water flow in the small water pipes from the top containers to public and private users. The study presents a calculation method based on Bernoulli's equation for fluid mechanics. The simplified form of the equation is the result of an adaption to Pompeii's conditions and has been used for the calculation of water velocity and the water quantity in water pipes when three geometrical variables are known, the head, the length of the pipe and the diameter of the pipe. The calculations of the water quantities in small water pipes have shown that less than half of the total incoming water quantity to the city was supplied for public use in the street fountains and the public baths, and that at least half was supplied for private use. This means that the water supply for some private users must have been considered from the beginning. The calculation method has only resulted in estimations, but the equation presented is exact and deserves to be used in the future as more exact values of the three geometrical variables are measured.

Keywords Pompeii · Water supply · Street fountains · Water quantities

Preamble

The water-supply system of Pompeii has been studied by many scholars and some of them have made an attempt to estimate the total amount of aqueduct water supplied to the city. There are two different methods to estimate the water quantity, from the supply side or from the demand side. Hans Eschebach estimated the water quantity supplied by

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the aqueduct. He based his calculation on the water inlet area of the aqueduct, 0.25 × 0.30 m, and an estimated water velocity of 1.0 m/s, arriving at 75 l/s (Eschebach 1983, p 101). Christoph Ohlig discussed instead the quantity of water used in the city. He hypothesized a water consumption of 200–400 l per person and day for a population of about 8000 people, giving a water-supply of 20–40 l/s to the city (Ohlig 1994). In an earlier study I have concluded that the total incoming water quantity in the aqueduct to Pompeii was smaller than previous research has indicated at 17 l/s Olson (Olsson 2020).

However, it still remains unclear how aqueduct water could reach all users, some of them at a far distance from the water towers, in a system based on gravity flow. The distribution of water in small lead pipes from the top containers to the water users has not been discussed in detail before, but in this study I will demonstrate how water could be distributed to reach all users, also at a far distance.

Introduction

The water-supply system in Pompeii delivered water to both public and private water users. This study will discuss the water supply in the small water pipes to public use in street fountains and to private use in houses and workshops. The study will present a calculation model to enable estimations of the water quantity in small pipes to users. The model will also show how decisive the distance between water tower and user is for the amount of water supplied.

Many scholars have studied the system and concluded that water was supplied to the city through an aqueduct to the *Castellum Aquae* and most agree that from there it was distributed in three main water pipelines. Duncan Keenan-Jones has suggested that there were only two main water pipelines and that the third was not a pipeline but rather an opening that supplied water to a basin directly below it (Keenan-Jones 2015). In an earlier study I have however argued that this could not have been possible, because in such a case most of the water would have been supplied to the basin and only small quantities to the two pipelines (Olsson 2020). The aqueduct water was led up to fill lead containers on top of a number of water towers, and from there it continued downhill from one tower to the next located at a lower level. All top containers also had connections to small individual lead water pipes to public and private users in the different districts of the city. However, it still remains unclear how and with what efficiency aqueduct water could reach all users, some of them at a far distance from the water towers, in a system based on gravity flow.

In a previous first study I have discussed how the system was designed to reach all water towers via the three main water pipelines (Olsson 2015). In a second study I have explored the question how balance was achieved in the top containers, in other words that the sum of the outgoing water flow from the top container was equal to the incoming water flow (Olsson 2020). I based this study on calculations of the water quantities in the three main water pipelines. This second study also concluded that the incoming water quantity in the aqueduct to Pompeii was smaller than previous research had indicated. The present third study will focus on the delivery of aqueduct water to public and private users: the small pipes that made it possible to satisfy every water user. The study will present a theoretical calculation method for water quantities in small water pipes and thereby approach the question of the varying efficiencies inherent to this distribution system.

The specific case of the water-supply system in Pompeii with communicating interconnections between a top container and a water user makes it possible to identify each part of the system as an independent unit. If the water quantities to individual users can be calculated with some accuracy it will be possible to discuss the priority in water supply to different districts and the prioritization observed between public and private users. The calculations will show how distance from a water tower had a decisive influence on the water quantity received in every location, limiting the flow. Water users located close to the water towers had a privileged position because the length of the water pipe had an influence on the water quantity supplied.

The distribution of water in small lead pipes from the top containers to the water users has not been discussed in detail before, mainly because such pipes, when found, were often removed during or after excavation. Only a few fragments of lead water pipes found in the streets have been recorded in archaeological investigations. Lead water pipes were not focused on as study objects in their own right, and so no documentation was undertaken as they were of so little interest.

The aim

In this study the focus is to explain the water flow in the small water pipes from the top containers to public and private users. The study will discuss previous research on water pipe dimensions and the Roman standards for lead water pipes. No new measurements of lead water pipes in Pompeii will be presented.

The aim of the study is to present a calculation method. It will however not be possible to calculate accurate values for water quantities based on this theoretical model when levels, lengths, and pipe dimensions are imprecise. Levels and lengths can be estimated with some precision but there will be uncertainty regarding the pipe dimensions and the complicated pipe distribution network inside the houses. The calculations will thus result only in estimations. The equation, and the mathematical connection that it yields, is otherwise exact and deserves to be used in the future when more exact measurements of pipe dimensions and lengths can be obtained. Thus, the contribution of the study does not reside in the quantities presented, but in the means to obtain them. A collateral result of the calculation is that it clearly demonstrates how different water users were served by the aqueduct depending on the position of their homes within the city.

The present study will discuss water pipe dimensions according to Roman standard, assuming that lead pipes in antiquity were manufactured according to the Roman standard presented in the literary sources.[1] The study presents calculations of water quantities based on these pipe dimensions and compares the results with investigations made by other scholars. An intention was to investigate the fragments of lead pipes kept in storage in Pompeii but this did not prove possible in either 2019 or 2020 for various reasons.

The location of public and private water users has been presented in previous research. The present study will discuss the connections between water towers and water users and thereby estimate the lengths of the water pipes.

The calculations will be imprecise not only due to uncertainties in pipe dimensions and pipe lengths but also because it is not known if all water users evidenced were supplied simultaneously. The date and continuance of the connections may have varied. Furthermore private water users were equipped with individual closing valves and could decide to

1 Frontin. *Aq.* 39–63.

Table 1 Dimension for small water pipes according to Vitruvius with measurements in cm presented by Fahlbusch (1989)

Width of plate in *digiti*	Name	Ideal external circumference in cm	Ideal external diameter in cm	Ideal external cross section area in cm^2
5	*quinaria*	9.3	2.9	6.8
8	*octonaria*	14.8	4.7	17.4
10	*denaria*	18.5	5.9	27.2

reduce the water quantity to the fountains in the house. Public water users were supplied with continuously flowing water. The unexcavated parts of the city most probably conceal further water towers and water users in addition to those known today.

Previous research on water pipe dimensions

The Roman standard for lead water pipes was first mentioned by Vitruvius in his *De Architectura*.[2] He describes standard dimensions for lead water-pipes, with ten standard sizes with names based on the circumference in *digiti*. The three smallest lead water pipes mentioned by Vitruvius, of special interest for the present study, were the five-finger pipe called *quinaria*, the eight-finger pipe called *octonaria* and the ten-finger pipe called denaria. (Table 1)

Vitruvius presented the width of the plate before bending, indicating the circumference of the pipe. He also gave the weight for a 10-foot plate in *pondus* where 1 *pondus* = 0.45 kg. Vitruvius' records of weights made it possible to calculate the thickness of the plates. The calculation shows that the lead pipes were very heavy and had a great thickness of the pipe walls (about 1.0 cm) irrespective of the size of the pipe. This is not reasonable for small water pipes because a five-finger pipe with an external diameter of 2.9 cm would then have had an internal diameter of only 0.9 cm. In my field investigations in Pompeii I have measured the dimension of one pipe fragment still *in situ* and found in *Via del Balcone Pensile*. The external diameters in two perpendicular directions were 4.0 cm and 5.0 cm respectively. The shortest inner diameter was 3.0 cm. My measurements indicate that this water pipe had been manufactured using a 0.5 cm-thick lead plate. In another study by Monteleone *et al.* presented below it was observed that the pipes found in Pompeii had a wall thickness between 0.4 and 1.0 cm (Monteleone et al. 2021). For the calculations of water quantities in small water pipes the present study will presume that the smallest lead pipes were made of 0.5 cm-thick plate.

Henning Fahlbusch has discussed the Roman standard for lead water-pipes (Fahlbusch 1989). He is of the opinion that Vitruvius assumed an ideal case with carefully manufactured circular pipes, although pipe fragments found in Pompeii had a pear-shaped form. The lead plate for making a pipe of five-finger size, *quinaria*, had consequently a width of 5 x 1.85 cm = 9.25 cm, resulting in a pipe with an external circumference of 9.25 cm and an external ideal diameter for a circular pipe of 2.94 cm. It follows that the cross-section area was 6.8 cm^2. For an eight-finger lead pipe, *octonaria,* the circumference was 8 x 1.85

[2] Vitr. *De Arch.* 8.6.4.

Table 2 Dimensions for ideal circular water pipes according to Frontinus/Fahlbusch

Diameter in *digiti*	Name	Ideal internal circumference in cm	Ideal internal diameter in cm	Ideal internal cross-section area in cm^2
$^{5}/_{4}$- *digitus*	*quinaria*	7.27	2.31	4.20
$^{6}/_{4}$- *digitus*	*senaria*	8.72	2.78	6.05
$^{7}/_{4}$- *digitus*	*septenaria*	10.18	3.24	8.22
$^{8}/_{4}$- *digitus*	*octonaria*	11.63	3.70	10.75
$^{10}/_{4}$- *digitus*	*denaria*	14.54	4.63	16.80
$^{12}/_{4}$- *digitus*	*duodenaria*	17.44	5.55	24.19

cm = 14.8 cm, and the diameter was 4.71 cm. The cross-section area was 17.4 cm^2. For a ten-finger pipe, *denaria,* the circumference was 10 × 1.85 cm = 18.5 cm, and the diameter was 5.89 cm. The cross-section area was 27.2 cm^2.

Later Agrippa introduced a new standard with 25 standard sizes described by Frontinus.[3] In this case, interest is in the water quantity flowing in the pipe rather than in the geometrical dimension of the pipe. Frontinus introduced a new meaning to the concept *"quinaria"*, now denoting the water flow in the pipe and simultaneously the nominal size of the 5-finger pipe. For all standard sizes he gave numbers for diameter in *digiti*, for circumference in *digiti* and for the capacity of water flowing in the pipe.

The smallest standard pipe, size 5, was given the nominal name "*quinaria*"

because the diameter was $^{5}/_{4}$- *digitus*. The new standard added ¼- *digitus* to each of the following sizes. The standard pipe, size 6, was called *senaria* and had a diameter of $^{6}/_{4}$- *digitus*, the size 7, *septenaria,* was $^{7}/_{4}$- *digitus* and so on for the first eight sizes.

Frontinus also gave numbers for the circumference in *digiti* for all standard sizes. A closer consideration of all his measures reveals that he described perfectly circular pipes where the circumference divided by the diameter gives the same result for all sizes: the quotient was 3.14 (pi). He used the term *perimeter* so it is reasonable that the circumference of a water pipe was the external measurement. It follows that the diameter given by Frontinus must be the external diameter. Interpreting Frontinus' numbers as representing internal diameter and circumference for ideal circular pipes, Fahlbusch translated his units of measurement to cm. Table 2 presents the six smallest sizes mentioned by Frontinus 5, 6, 7, 8, 10 and 12 finger pipes with circumference, diameter and cross-section area calculated by Fahlbusch (1989, Table 4, p. 142). His idea that Frontinus discusses inner measurements appears unconvincing to the present author.

Robert Rodgers has provided an opinion in his commentary that a manufacturer would have had difficulties in attaining the accuracy in the production that was required by the numbers given by Frontinus (Rodgers 2004, p. 223).

This new standard defined intermediate sizes compared with the earlier standard. Obviously the new Roman standard for water pipes, mentioned by Frontinus, had smaller dimensions than the old standard described by Vitruvius. A water-pipe with the same denomination, e.g. 5-finger or *quinaria*, had a different capacity in the two systems. It is

3 Frontin. *Aq.* 39–63.

worth noting that Vitruvius presented the old standard from the perspective of the pipe manufacturer but Frontinus had the user's view when introducing the new standard.

Archaeological evidence of water pipes in the streets is rare. As illustrated in an earlier study, only twelve fragments were found in properly documented excavations and only three of them were measured (Olsson 2015). Therefore the present study will be only theoretical and discuss the smallest water pipe called *quinaria*. Calculations of water quantities in larger water pipes will show higher values. A water pipe called *senaria* will supply double the amount of water at the same head and pipe length as a pipe called *quinaria*, a water pipe called *septenaria* more than three times more. It is possible that water pipes of different sizes were used to supply water to different users. The present study will only discuss the smallest water pipe called *quinaria* based on the new standard as described by Frontinus and interpreted as having an external diameter of 2.31 cm and a circumference of 7.27 cm. It follows that my estimation of internal diameter, 1.31 cm is calculated as the external diameter of 2.31 cm less the anticipated thickness of the lead plate of 0.5 cm as presented in Table 3.

The reduced cross-section area used in my work reflects the reality of pipes found in Pompeii, that they have a pear-shaped form and therefore water pipes had a smaller cross-section area, perhaps 75% of the ideal.

It should be remembered that the calculations of water quantities in small water pipes is hindered by the fact that the finds of pipe fragments have generally not been recorded in detail in archaeological publications, and thus the data advanced in my calculations are based on Frontinus' standards, rather than on finds.

The calculation method

The calculations of the water quantities will be made for a number of small pipes leading from the top container of a water tower to street fountains and private houses and workshops. The theoretical background for the calculations can be presented as follows. For any liquid running in an ideal pipe free of any friction and other losses, the total energy in every single point is constant and can be described by Bernoulli's equation saying that the sum of the different forms of energy that can affect a fluid, the pressure, the velocity and the head, is constant. The pressure is the atmospheric pressure on the open water surface, the velocity is the water velocity in the pipe and the head is the difference in level between the summit of the top container of a water tower and the water level at the public street fountain or the private water user respectively. This may be expressed as:

$$p + \frac{\rho u^2}{2} + \rho g h = constant \tag{1}$$

where p is the atmospheric pressure on the water surface on the summit of the water tower and at the water user, ρ is the density of water, u is the water velocity in the pipe, g is the gravitational acceleration and h is the head above some fixed datum.

The dimensions of Eq. (1) are energy per unit volume of water.

Bernoulli's equation will be applied for the specific case of the water-supply system in Pompeii with communicating vessels consisting of the interconnection between a top container and a water user.

Table 3 Dimensions for ideal circular water pipes according to Frontinus/Olsson

Diameter in *digiti*	Name	Ideal external circumference in cm	Ideal external diameter in cm	Ideal internal diameter in cm
$^5/_4$- *digitus*	*quinaria*	7.27	2.31	1.3

The total water energy per unit volume on the summit of the top container, E_{tower}, is as follows:

$$E_{tower} = p_{tower} + \frac{\rho u^2}{2} + \rho g h_{tower} \tag{2}$$

The total water energy per unit volume at the water user, E_{user}, is as follows:

$$E_{user} = p_{user} + \frac{\rho u^2}{2} + \rho g h_{user} \tag{3}$$

Normally there are losses in the pipe connection partly due to friction losses in the contact between the pipe and the running water and partly due to so-called single-case losses because of pipe bends in the system.

Friction losses are a mathematical function of the length and the inner diameter of the water pipe connection multiplied with the so-called friction factor λ, which depends on the inner roughness on the water pipe connection and the speed of the flow. The friction factor for ancient lead water pipes is not known. For very rough modern pipes the friction factor is between 0.03 and 0.04. It is possible that water pipes in antiquity had even larger friction which then would have resulted in lower water velocity and less water supply. In a recent published study, Monteleone et al. have tabled values of the friction factors for Roman lead pipes between 0.09 and 0.04 for small pipes (Monteleone et al. 2023). In the calculations in this study the figure 0.04 will be used for all small pipes. A sensitivity analysis has been made for larger friction with a factor 0.06 and 0.09 respectively and the result is tabled in Appendix 1 showing water quantities to street fountains reduced on average by 17 % and 32 % respectively. The friction losses must have been very large because the water pipelines in Pompeii were very long. The friction losses are as follows:

$$\Delta p_{friction} = \frac{\lambda L \rho u^2}{2D} \tag{4}$$

where λ is the friction factor, L is the connection length and D is its diameter.

Single-case losses are dependent on the geometry of the water pipe connection as a result of the lead pipe production method, and of the single-case loss coefficient, not known to us for ancient lead water pipes. The single-case losses are as follows:

$$\Delta p_{single} = k\frac{\rho u^2}{2} \tag{5}$$

where k is a loss coefficient dependent on the precise geometry.

The total water energy on the summit of the top container is equal to the total water energy at the water user plus the losses in the water pipe. The atmospheric pressure on the summit of the water tower (p_{tower}) and at the water user (p_{user}) are the same and can be eliminated. The water velocity at the water surface in the water tower is zero so the term $\frac{\rho u^2}{2}$ at the tower can also be eliminated. Finally we assume there is no change of pipe size, so the velocity u remains the same along the whole connection.

The applied version of Bernoulli's equation where the total water energy on both sides are equal is shown below:

$$gh_{tower} = \frac{\rho u^2}{2} + \rho gh_{user} + \frac{\lambda L \rho u^2}{2D} + nk\frac{\rho u^2}{2} \tag{6}$$

Here, n is the number of cases of single losses, for example the number of pipe bends.

To be able to calculate the water quantity it is now necessary to transform the equation and first calculate the water velocity in the pipe. The applied version of Bernoulli's equation will be used for the calculation of the water velocity in the pipe introducing the head h as the difference in water levels between the water tower (h_{tower}) and the water user (h_{user}).

The simplified equation is shown below:

$$u = \sqrt{\frac{2gh}{1 + \frac{\lambda L}{D} + nk}} \tag{7}$$

The single-case losses could be disregarded in the estimations because they were small compared with the very large friction losses.

The water quantity will be calculated as the water velocity multiplied with the area of the cross-section of the pipe. The calculations will investigate the three geometrical variables mentioned above.

The head h is the difference in water level between the top container of a water tower and the opening of the street fountain. The head will be based on the measured heights of water towers (Olsson 2015).

The length of the water pipe L will be measured and estimated as the sum of the height of the water tower with the top container and the length of the water pipe in the street up to the mouth of the street fountain or up to the entrance of the house.

The diameter of the water pipe D will be chosen from the new standard sizes as described by Frontinus. The calculations will be made for a 5-finger pipe, because, as will be shown, larger pipes would have emptied the system and the available water quantities could not have reached all water users.

Estimations of water quantities

The calculation method presented above will be used for estimations of water quantities in small water pipes for public and private use. The aqueduct water for public use went to street fountains and baths. The top containers of the water towers had individual water connections to all public and private users. At our present state of knowledge there were 42 connections to street fountains, five connections to public baths, and at least 91 or perhaps 103 connections to private houses and workshops; thus a total of 138 to 150 water connections from 14 water towers. This means that on average a water tower could have had more than ten water connections, and further water users could have been connected in the as-yet unexcavated parts of the city. With the simplified calculation method presented above the water quantities in small water pipes could be calculated if the three geometrical variables, head, length of pipe and pipe diameter, could be estimated with some accuracy. However, it must be remembered, that all three variables have uncertainties and need detailed on-site observations to approach better accuracy.

The head is the difference in level between the top container and the delivery point in the street fountain as mentioned before. In the estimations below the head is based on the measured heights of water towers plus the estimated heights of the top containers, to which the effect of the slope of the street needs to be added (Olsson 2015). If the base of the tower stood on higher ground than the arrival point at the user, this height difference must be added to the height of the tower. If, on the contrary, the tower stood on lower ground, the difference must be subtracted.

The length of the connection pipe is estimated from the summit of the water tower plus the distance to the water user measured on a 1:5000[4] scale map and presented for street fountains in Appendix 1 and for houses and workshops in Appendix 2. The pipe length is not only the horizontal distance to the water user but also the length of the pipe going down in the ground at the foot of the water tower, under the street in many cases and up again at the water user. This small length of the water pipe is not known and has been estimated to one metre and in some cases to two metres.

The diameter of the 5-finger water pipe is estimated from the new standard size, as described by Frontinus, translated to the metric system by Fahlbusch but interpreted by the author as external diameter. As described above, 0.5 cm corresponding to the estimated thickness of the pipe wall is subtracted to obtain the hypothetical internal diameter. The pipes found were not circular but had a pear-shaped cross-section so the cross-section area was estimated to 75% of the ideal. Actual pipe dimensions are unknown.

The simplified calculation method is insufficient for the calculation of the quantity of aqueduct water actually available in the private houses and workshops, because of the complex distribution system inside the house with a number of bends, distribution boxes and closing valves creating single-case losses. To at least get an estimation of the potential of delivery, the distance from a possible water tower to the entrance of each house and workshop has been measured on a 1:5000 scale map and presented in metres in Appendix 2. The length of the water pipe is significant for the estimation of the water quantity to a house or to a workshop but it should be remembered that the actual numbers used in the calculation give only a very rough estimation of the real value.

Calculation of water quantities to street fountains

Both private houses and street fountains were supplied by means of small water pipes. Below, the water supply to street fountains will be discussed first. The possible pipe connections to street fountains were dependent on their locations and on the head between the top container of a water tower and the level of the street fountain.

[4] Ray Laurence's base map in Laurence (1994).

Location of street fountains

The street fountains were supplied with water from the top container of a water tower through an individual water pipe. Hans Eschebach has presented the 42 street fountains found in the city indicating their location (Eschebach 1983, p. 90 and Table 2). Together with Thomas Schäfer he has also numbered the street fountains from nos. 1 to 42 (Eschebach and Schäfer 1983). The street fountains are located all over the city. In most cases it is unknown which fountain connected to which tower.

In an earlier study, I have demonstrated the route of the three main water pipelines and shown the most plausible connection between the water towers and the public fountains in the area served by it. The eastern water pipeline distributed water to the top containers of water towers nos. 1, 2, 3, 4, 5, 6 and 14 and also to three unknown towers in the not-yet excavated parts of the city (Olsson 2015). There were 26 street fountains connected to these ten towers. Similarly, the central water pipeline fed water towers nos. 7, 9 and 11 and had seven street fountains connected. The western water pipeline had four water towers, nos. 12, 13, 8 and 10 with nine street fountains. The possible water pipe connections to street fountains as presented in an earlier study are shown in Fig. 1. It is not possible to verify the connections in antiquity between the water towers and the street fountains. In a recent study, Monteleone et.al. have analysed different connections for each fountain (Monteleone et al. 2023). Four possible connections to street fountain no. 23 from four different water towers nos. 2, 3, 8 and 9 are discussed and the most probable connection is assumed to be from water tower no. 2. The four water towers are all possible because they are the closest to the street fountain. The three towers nos. 2, 8 and 9 have all a high level at the top and would supply more water to the fountain. The present author suggests a connection from water tower no. 3 because Nappo (1994) found a ditch full of *lapilli* in *Via degli Augustali* all the way to street fountain no. 23 (Olsson 2015). The actual connections in antiquity are not known. The water quantities presented by Monteleone et al. differ from the figures in this article but this study will only demonstrate a theoretical calculation method, not accurate values for water quantities.

In a second study (Olsson 2015), the present author pushed the analysis of the street fountains further. Their dimensions were measured and the capacity of their basins calculated. The head, based on the location in the city, was attributed to each fountain and their connection to a probable water tower was decided by the assumption of the shortest distance. The present study will extend the understanding of the system by exploring the water quantities in the pipe connections, dependent on the distance covered, on the head between the level of the top container and the level of the street fountain, and on the size of the pipe.

Water quantities delivered to street fountains

According to the theoretical method presented above, the calculation of the water quantities delivered to the street fountains is based on the three geometrical variables:

The head (h) is resulting from a calculation involving four height measurements. Most important is the measured height of water tower. To this number the estimated heights of the top containers should be added. Further the effect of the slope of the street needs consideration. Finally, the measured height up to the mouth of the street fountain should be subtracted. It could be argued that the measured heights of the towers lack accuracy

Fig. 1 Probable pipe connections to street fountains marked by solid lines and plausible connections by dotted lines. Drawing by author modified from Ray Laurence's base map in Laurence 1994

because some of the water towers might have been higher than today. However, the height of water tower no. 1 cannot in antiquity have superseded its present height: the actual level at its summit is so close to the level of the opening in *Castellum Aquae* that gravity driven water flow would not have been possible had the tower been higher.

The length of the small pipe (L) is the sum of the measured height of the water tower plus the distance between the water tower and the street fountain, plus the measured height up to the mouth of the street fountain, and plus the estimated length of the pipe down into the ground and up again.

The diameter of the small pipe (D) is not known. The calculation has been made for a 5-finger pipe, defined by the present author as described above.

When the water velocity (u) has been calculated it has been multiplied with the reduced area (A) of the cross-section of the water pipe to arrive at an estimation of the water quantity (Q).

If water tower no. 5 is taken as example, we obtain the following. Located on *Via dell'Abbondanza* at the corner of *Vicolo di Paquius Proculus*, water tower no. 5 supplied water to four street fountains nos. 3, 4, 5 and 42, as shown in Fig. 2. Most probably, it also supplied water to five private houses and a not-yet excavated water tower in *Regio* I.

In an earlier study, I have discussed a pipe fragment found by Nappo in the western pavement of *Via dell'Abbondanza* between water tower nos. 4 and 5 with a size estimated by him as *denaria* (Olsson 2020). It stands to reason to take this pipe fragment as a surviving fragment of the eastern water pipeline between the two towers. The head difference between the two towers amounts to 2.4 m and the length of the pipe to 130 m. According to the calculation made possible by the simplified equation presented above, this means that water tower no. 5 received 1.4 l/s aqueduct water from water tower no. 4 and delivered 0.8 l/s to water tower no. 6 in a smaller pipe possibly size *octonaria*. As demonstrated in my earlier study, the pipelines must have had smaller and smaller dimensions down the system

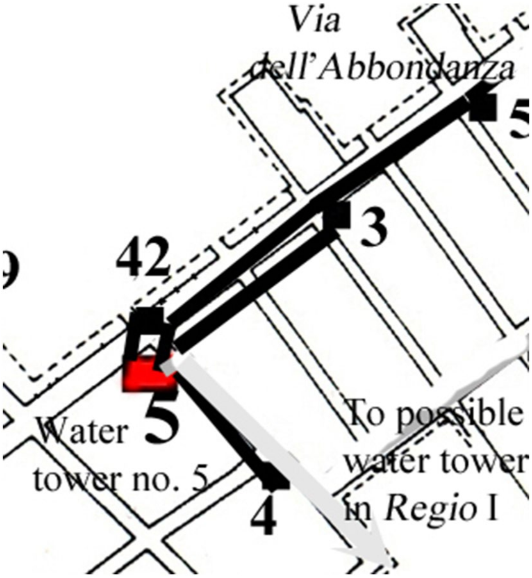

Fig. 2 Probable pipe connections to four street fountains (nos. 3, 4, 5 and 42) from water tower no. 5

to achieve and keep the balance of the system. It results that only 0.6 l/s was available for the supply to water users and the not-yet excavated but possible water tower in *Regio* I.

It is worth noting that the calculation method presented in this study, based on the three variables of the aqueduct system, allows insight not only into the capacity of the system, but also contributes to further understanding of the information given to us by Frontinus. The calculation of water quantities supplied from water tower no. 5 to street fountains nos. 3, 4, 5 and 42 has been chosen as illustration (Table 4).

The table uses the linear pipe definitions given by Frontinus in two different understandings, as external measurements by the present author, as internal by Fahlbusch. For the numbers advanced by the author, the thickness of the lead plate, assumed as 0.5 cm, has been subtracted to obtain an estimated interior diameter and the ideal rounded cross-section with a cross-section area recalculated for a pear-shaped pipe. A consideration of the results demonstrates that the pipe dimensions only fit within the available supply of water to water tower no. 5 (0.6 l/s) if Frontinus' pipe diameter is interpreted as external as advanced by the author.

If the water pipes to street fountains had been larger, as indicated by the numbers given by Fahlbusch, the water supply would have emptied the water tower's container and aqueduct water could not have reached further users down the system. The calculated values of water supply, suggested by the author, imply that the four street fountain basins would fill up from empty to full in 1.5 to 3.5 hours.

The supply must have differed considerably from basin to basin. Due to the friction factor, the potential of water delivery in small pipes varies with the length of the pipes. The velocity of the water delivery to users close to the tower is less affected by this factor than that to far-off users. A few of the street fountains are located very close to a water tower but most of the fountains are connected with a very long water pipe, on average 70 m. Due to the friction losses, a water user close to a water tower connected with a short water pipe will be supplied with a greater water quantity than

Table 4 Water quantities to street fountains nos. 3, 4, 5 and 42 presenting two different understandings of Frontinus' *quinaria*- standard

Street fountain no	3	4	5	42
Head	4.2 m	6.3 m	5.1 m	3.4 m[a]
Length of pipe	85 m	80 m	165 m	13 m
Diameter of pipe—Frontinus' *quinaria* understood as internal by Fahlbusch	2.31 cm	2.31 cm	2.31 cm	2.31 cm
Water quantity calculated according to Frontinus/Fahlbusch	0.23 l/s	0.29 l/s	0.18 l/s	0.47 l/s
Diameter of pipe—using Frontinus' *quinaria* as external minus thickness 0.5 cm according to the author	1.3 cm	1.3 cm	1.3 cm	1.3 cm
Water quantity calculated according to Frontinus/the author	0.07 l/s	0.09 l/s	0.06 l/s	0.16 l/s

[a]A mathematical error in the first study, Olsson (2015), has been observed in a review indicating that the head between water tower no. 5 and the opening in street fountain no. 42 should be 3.4 m instead of 3.2 m. Consequently, the correct calculation of the water quantity to this fountain should be 0.162 l/s (rounded to 0.16 l/s) instead of 0.157 l/s (rounded to 0.16 l/s). The figures in Appendix 1 have been corrected accordingly. The height 0.8 m of the top container of water tower no. 5 is estimated in Olsson (2015), Table 4, to be smaller than the width of the container in order to have sufficient stability

a water user at a greater distance, provided that they are connected with pipes of the same dimension.

Water quantities to four street fountains, nos. 19, 18, 22 and 1, located at the foot of and close by water towers nos. 1, 2, 3 and 4, are presented in Table 5, calculated by the author. As earlier in this study, the calculation uses the unit of a 5-finger pipe with metric dimensions given by Fahlbusch but interpreted by the author as external and considering the lead plate thickness as 0.5 cm and the cross-section as pear-shaped.

Table 5 demonstrates that the length of the pipe had a significant influence and that the water quantities to street fountains located close to a water tower were higher than to street fountains at a far distance as shown in Table 4. The estimated water quantity according to the author to each of the four street fountains located close to a water tower, on average 0.24 l/s, would have filled the basin by the foot of the tower in 1 to 1.5 hours.

Calculation of water quantities to the street fountains located at a far distance from the water towers' top containers cannot be achieved with the same accuracy as those close to the towers mentioned above, as the exact routes of the long pipes are not known. For these examples the distance from the possible water tower has been measured in the same way as mentioned above on a 1:5000 scale map. After adding the height of the water tower, the result, the estimated length of the pipe is presented in Appendix 1.

There were seven street fountains located within 20 m from the water tower. Estimated water quantities as tabled in Appendix 1 are between 0.14 and 0.27 l/s for these seven fountains, on average 0.20 l/s and in total 1.39 l/s. Five street fountains were located 20–50 m from the tower with estimated water quantities between 0.06 and 0.13 l/s, on average 0.09 l/s and in total 0.47 l/s. Ten street fountains located 50–100 m from the tower had estimated water flows between 0.05 and 0.13 l/s, on average 0.08 l/s and in total 0.82 l/s. Finally, 14 street fountains located at a distance of 100 m or greater were supplied with between 0.04 and 0.08 l/s, on average 0.06 l/s and in total 0.84 l/s.

Table 5 Water quantities to street fountains nos. 19, 18, 22 and 1 according to the author

Water tower no	1	2	3	4
Street fountain no	19	18	22	1
Head	7.0 m	6.6 m	6.2 m	6.2 m
Length of pipe	10 m	15 m	18 m	10 m
Diameter of pipe—standard as external minus thickness 0.5 cm according to author	1.3 cm	1.3 cm	1.3 cm	1.3 cm
Reduced area due to pear-shaped pipe	1.33 cm^2	1.33 cm^2	1.33 cm^2	1.33 cm^2
Water velocity	2.01 m/s	1.61 m/s	1.46 m/s	1.98 m/s
Water quantities according to the author	0.27 l/s	0.21 l/s	0.19 l/s	0.26 l/s

For 36 street fountains the total estimated water supply was calculated to 3.52 l/s, on average 0.10 l/s. Six street fountains were connected to unknown water towers.

The total water quantity supplied to all street fountains can be estimated to 4.2 l/s.

Comparison with a different method of calculating capacity

In a recent study Maria Monteleone, Martin Crapper and Davide Motta have discussed the water supply to street fountains in Pompeii and the water quantities involved (Monteleone et al. 2021). They have used measurements related to two features of the street fountains, the discharge of water from the street fountains through their overflow channels and the potential flow velocity of the water jet entering the basin by the spout hole, as shown in Fig. 3. Their results will be discussed below and compared to the calculations of water quantities to street fountains by means of the method suggested in this study.

The street fountains' overflow channel, which directed the excess water from the street fountain onto the street, were measured and the cross-section profile reconstructed. Subsequently, the discharge of water was calculated at three different levels, 1 cm above bottom, half of the cross-section height, and entire cross-section height. Based on these data a minimum, an intermediate and a maximum water discharge from each street fountain was calculated. Accordingly, in the case of the four street fountains connected to water tower no. 5, Monteleone *et al.* presented the numbers and results as shown below (Table 6).

A comparison with Table 4, above shows that the minimum amounts calculated by Monteleone *et al.* accords fairly closely with the water quantities estimated by the author for the same street fountains.

Monteleone *et al.*'s calculation of the water quantities based on dimensions of the overflow channels estimated the total water supply to 39 street fountains to 3.1 l/s, 16.8 l/s and 46.0 l/s for the minimum, intermediate and maximum discharge respectively. They concluded that the minimum and intermediate discharge might be more probable than the maximum. The water quantities in the minimum case are in line with the figures presented in this article.

In order to verify the corresponding water quantities supplied to the street fountains

Monteleone *et al.* also estimated the dimensions of the water pipes based on the size of the spout orifice, the opening in the relief stone of the street fountain, through which the supply pipe delivered aqueduct water to the basin. They measured two perpendicular diameters of the orifice. The internal diameter of the supply pipe was calculated from the

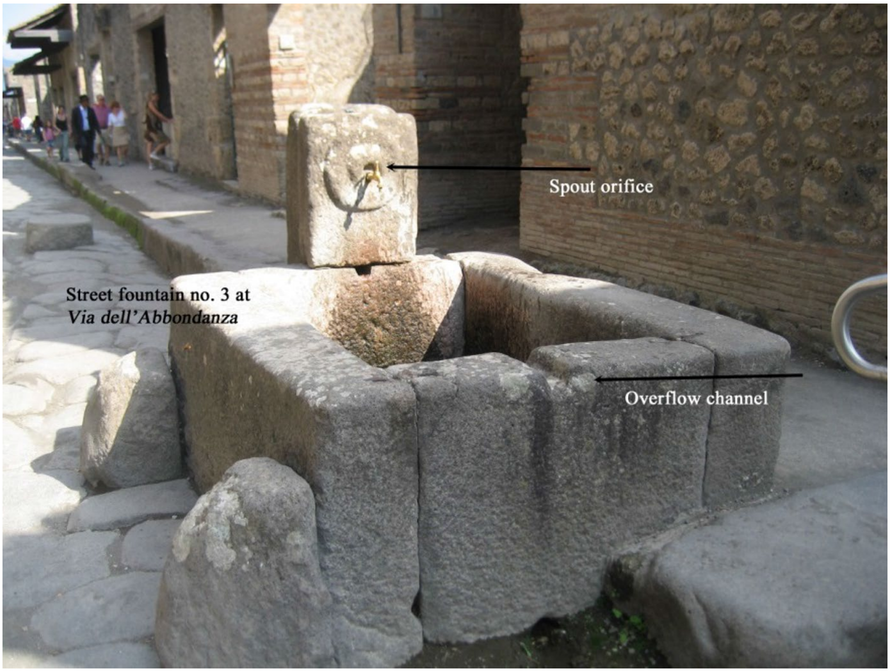

Fig. 3 Street fountain no. 3.The features measured by Moteleone et al. are indicated

Table 6 Water quantities to street fountains nos. 3, 4, 5 and 42 according to Monteleone et al. 2021, Tables 1 and 4

Street fountain no	3	4	5	42
Width of overflow channel	11.0 cm	8.0 cm	13.0 cm	12.0 cm
Height of overflow channel	6.0 cm	2.5 cm	7.5 cm	5.0 cm
Water quantity—intermediate	0.66 l/s	0.14 l/s	0.44 l/s	0.35 l/s
Water quantity—minimum	0.12 l/s	0.10 l/s	0.03 l/s	0.08 l/s

average diameter of the spout orifice minus an assumed pipe thickness of 0.5 cm. The average internal diameter of the supply pipe for 29 fountains was calculated by Monteleone *et al.* to 3.31 cm. The water quantities supplied to the street fountains for all connections examined were between 0.1 and 3.3 l/s (Monteleone et al. 2021).

The estimated water quantities calculated by the present author tabled in Appendix 1 are much smaller, only between 0.04 and 0.27 l/s, supplied with a small pipe with an internal diameter of only 1.3 cm. Larger pipes would result in higher water quantities which could have emptied the top container and water could not have reached all water users down the system.

Calculation of water quantities for private use

Location of private users

Water for private use was distributed to some private houses and to workshops. The number of houses that were connected to the water-supply system is not known, but can be estimated on the basis of lead-pipe fragment presence. In his city plan, Hans Eschebach indicated 63 houses which to his knowledge were connected to the public water-supply system (Eschebach 1983, Table 5). He also identified 46 workshops with considerable water use, but without mentioning if these workshops were connected to the system or if they collected water in a different way. Eschebach has only indicated in which city block the houses and workshops were located without specifically mentioning the name or address of each individual house or workshop. Later, in her doctorate thesis of 2001, Gemma Jansen investigated with a metal detector and listed 91 houses supplied with aqueduct water (Jansen 2002). In her number she included some workshops. Jansen has given the name or address for all 91 houses. In the present study, all houses, many of which, were formerly identified only by name, are identified by location, i.e., with the numbers of their main entrances. The resulting list, compiled in *regio*-order, is presented in Appendix 2.

Table 7 presents a comparison between the number of houses and workshops identified by Jansen and by Eschebach. The first column shows the 91 houses connected to the water-supply system according to Jansen. These houses numbered 1- 91 in Appendix 2, are shown in blue in Fig. 4. The second column shows the 63 houses indicated by Eschebach to be connected to the system in each *regio*. He also identified 46 workshops with a considerable water use shown in the third column.

In my study of Eschebach's city plan I have found twelve houses not mentioned by Jansen. These twelve houses are shown in green in Fig. 4. Many of the twelve houses are located on the outskirts of the city, five are in *Regiones* II and III in the south-east around water tower no. 6, three in *Regio* VI in the north-west close to water tower no. 13 and another two in *Regio* VIII in the south. Only two of the 12 houses are located in the central part of the city in *Regiones* VI and VII.

The result is that there might have been at least 91 + 12 (in total 103) houses connected to the water-supply system. In *Regiones* I and VII the total number mentioned by Eschebach is larger than that presented by Jansen probably because Eschebach included water-requiring workshops although lacking explicit proof of their connection to the aqueduct system.

It is obvious from Fig. 4 that individual water-supply to houses and workshops is more frequent in the north-western part of the city and less frequent in the south-east.

It is unknown in most cases which water tower supplied water to which private houses and workshops. The water pipe connection was dependent on the head between a water tower and the house and on the distance from tower to house. In this study the city has been divided into water supply districts around each water tower. It is possible that the individual pipe connection came from the water tower in the district as shown in Fig. 5.

Water quantities to a private house and a workshop

The calculation of the water velocity and the water quantity to a private user is difficult because of the complex distribution system inside the house with distribution boxes and

Table 7 Water supply for private use to houses and workshops

Regio	Number of houses and workshops connected to the system acc. to G. Jansen	Number of houses connected to the system acc. to H. Eschebach	Number of workshops with considerable water use acc. to H. Eschebach	Number of houses acc. to H. Eschebach but not mentioned by G. Jansen
I	9	5	11	–
II	3	7	–	4
III	1	2	–	1
IV	–	–	–	–
V	8	6	2	–
VI	24	19	6	4
VII	25	13	16	1
VIII	6	5	2	2
IX	15	6	9	–
TOTAL	91	63	46	12

closing valves creating single-case losses, on top of the friction losses occurring in the pipes leading to the houses and included in the calculation. It will be assumed that the water pipe had the same dimension all the way from the water tower to the front of the house and the calculations will only be made to this point knowing that the actual water velocity and water quantity must have been lower inside the house. It should also be emphasized that, as demonstrated by the examples below, the pipe connection to a house did not always come in through and under the *fauces* as assumed in the method.

The street crossing of *Via del Vesuvio/Via Stabiana* and *Via della Fortuna/Via di Nola* had a privileged position in relation to the aqueduct water-supply system, situated along and close to the early part of the pipeline system. Private houses and workshops close to this street crossing were probably supplied from water tower no. 2, the sturdiest of all and thereby probably once equipped with the most capacious top container. Two houses close to water tower no. 2 are chosen to exemplify the method: house V 1,23.26.10, *Casa di Caecilius Iucundus* and workshop VI 14,22, *Fullonica di Vesonius Primus*. The water entries and interior lines of both are investigated in earlier scholarship as presented below. To discuss the water pipe connection to these two houses it is necessary to consider the slope of the street. The street *Via del Vesuvio/Via Stabiana* is steeply sloping which means that tower no. 2 is situated downhill in relation to the two houses. The pipes descending from the top containers had to return up the slope to reach their destinations (Fig. 6). The level at the street crossing of *Via del Vesuvio/Via Stabiana* and *Via della Fortuna/Via di Nola* is + 32.4 m masl and at the street crossing of *Via del Vesuvio* and *Vicolo di Mercurio/Vicolo delle Nozze d'Argento* is + 34.7 m masl. This upward return reduces the head assuming that the slope is constant between the two street crossings. The levels in front of the two houses have been calculated to + 33.7 m masl. The head to *Casa di Caecilius Iucundus* is reduced with 33.7–32.4 = 1.3 m, and to *Fullonica di Vesonius Primus* with 33.7–32.4 = 1.3 m due to the slope upwards.

The system inside the house *Casa di Caecilius Iucundus* has been described and reported by Arja Karivieri and Renée Forsell (Karivieri and Forsell 2007). This is a double house with one small and one large *atrium*. The water was supplied from the top container

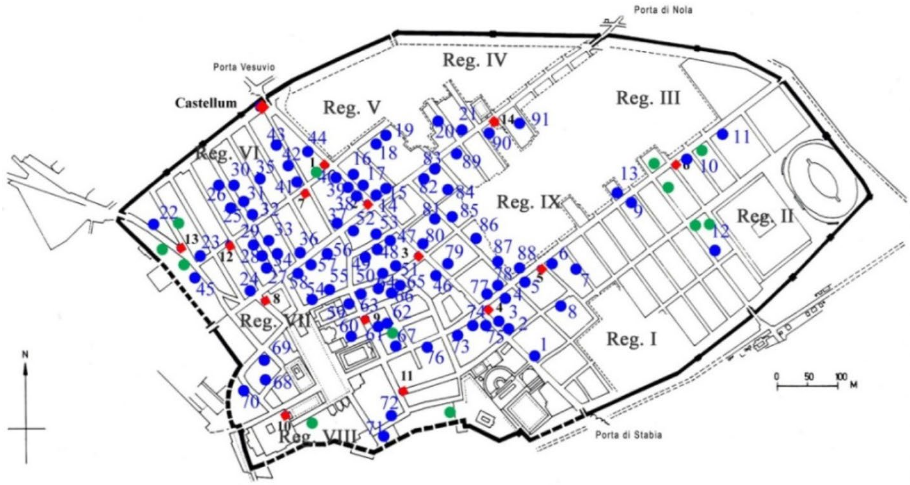

Fig. 4 Locations of distributing water towers numbered 1–14 in red, and 91 private houses according to Jansen (2002) numbered 1–91 in blue plus twelve private houses according to Eschebach (1983, Table 5) in green. Drawing by author modified from Ray Laurence's base map in Laurence (1994)

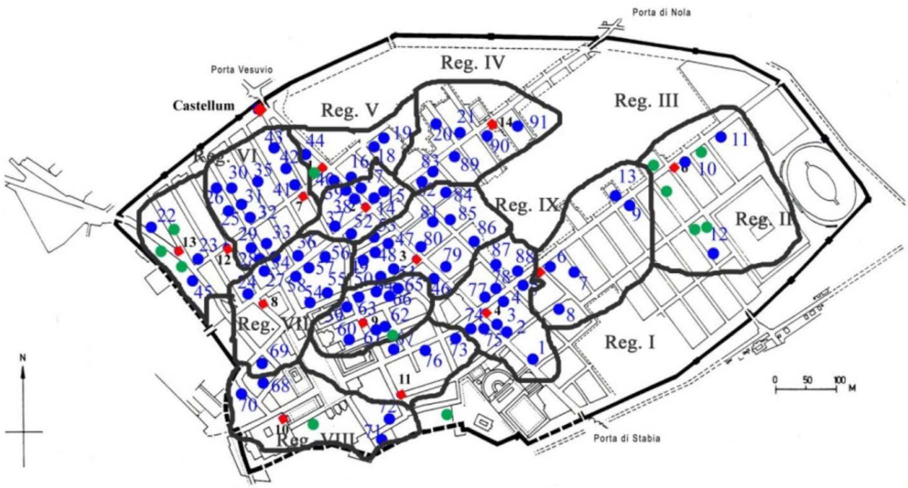

Fig. 5 Possible water supply districts in the city for pipe connection serving private use. Drawing by author modified from Ray Laurence's base map in Laurence 1994

on water tower no. 2 and most probably passed beneath the street pavement by the tower and uphill in a pipe in the eastern pavement all the way up to the house. It was brought into the north house through a pipe along the north wall of *taberna* V 1, 22. The pipe had a distribution box in the *atrium* of the north house connecting a pipe to its *impluvium* fountain. Further on inside the north house, another distribution box forked the line in two, one leading to the kitchen and the other turning south to a distribution box in the *peristyle* of the south house. It forwarded water both to the *peristyle* and *atrium.* The water pipe had presumably the same dimension all the way to the front of the house and the calculation has been made only to this point knowing that the actual water quantity must have been reduced inside.

Miko Flohr investigated water management in all excavated Pompeian laundries, some of which were originally built as domestic houses and later, perhaps after the earthquake, rebuilt into combined residential and commercial houses (Flohr 2011). One such house close to the street crossing, *Fullonica di Vesonius Primus*, was supplied from a water connection pipe from the aqueduct system. Gemma Jansen, who has studied and reconstructed the water distribution in seven houses in Pompeii, included this laundry in her study (Jansen 2001). She described how the water entered *Fullonica di Vesonius Primus* in the north-east corner of the house beneath its perimeter wall and the kitchen.[5] Water was then distributed to two fountains in the *atrium*. The pipe then continued then along the north wall and the corridor towards the laundry in the back of the house.

Water quantities for private use to all houses and workshops

The water quantities calculated up to the front of the two houses (Table 8) were estimated to between 0.10 l/s and 0.11 l/s respectively but would have been smaller due to the complexity of the water distribution inside the house. The two investigated houses were both located close to water tower no. 2. The length of the pipe is a significant factor influencing the water quantity to the house. A house located close to a water tower would have been supplied with a greater water quantity than a house located at a far distance, assuming they were connected with water pipes of the same dimensions.

There were 28 houses located within 50 m from the water towers. They might have had an estimated water quantity as the one calculated for the *Fullonica di Vesonius Primus*, or 0.11 l/s. In total the 28 houses could have been supplied with 3.08 l/s.

There were 22 houses located 50–100 m from the closest water tower and they might have had an estimated water quantity of 0.10 l/s as calculated for *Casa di Caecilius Iucundus*. In total these 22 houses could have been supplied with 2.20 l/s. Many (37) of the houses were located at a distance of 100–200 m. They were supplied with an estimated 0.08 l/s or 2.96 l/s in total. Only four houses were more than 200 m distant and might have been supplied with 0.06 l/s or 0.24 l/s in total. All 91 houses were possibly supplied with a total of 8.5 l/s of aqueduct water or on average 0.09 l/s per house.

Now, if the water quantity supplied to all private houses and workshops was less than 0.09 l/s on average, the total water quantity for private use, supplied to the 91 or perhaps 103 private houses and workshops, could be estimated to less than 9 l/s. It follows that a great deal of the total water supplied to the city was used for private use but it is not known if all water users evidenced were supplied simultaneously. The date and continuance of the connections may have varied. Furthermore, private water users were equipped with individual closing valves and could decide to reduce the water quantity to the fountains in the house. When valves were closed in houses water would flow over from the top containers of the water towers onto the streets. Water could also have been supplied to houses and workshops in as-yet unexcavated parts of the city.

[5] In Jansen's (2001) figure the pipe seems to come from the north. The interpretation by the present author is that the workshop was supplied from water tower no. 2 located to the south.

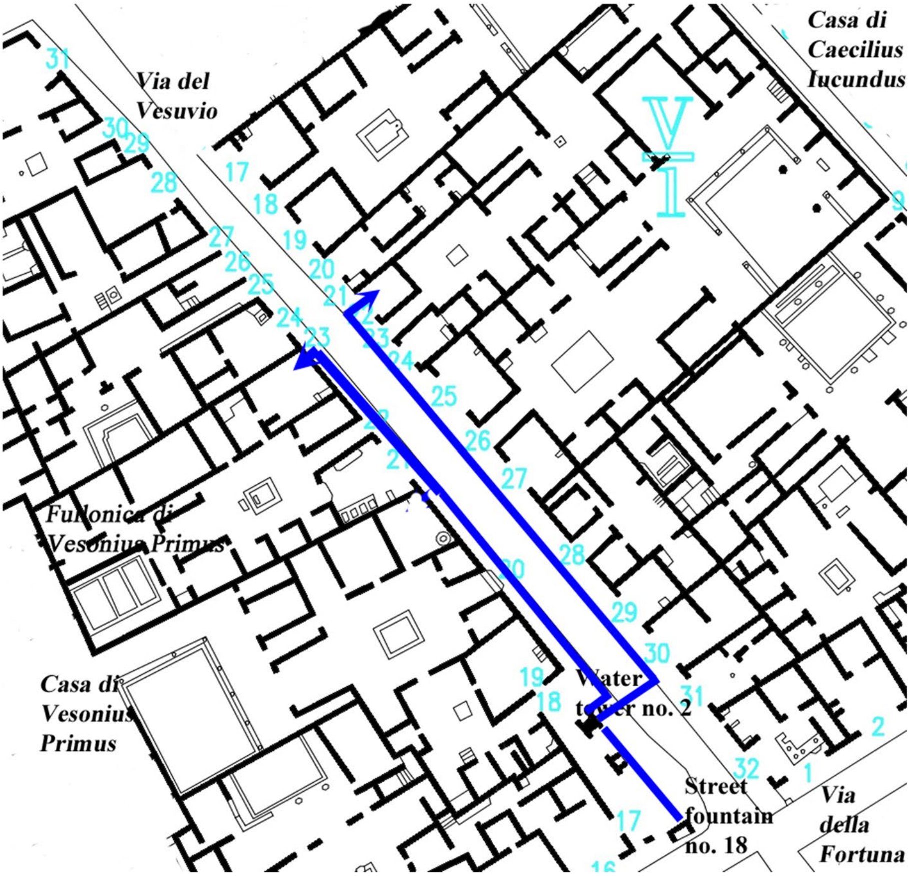

Fig. 6 The street crossing of Via *del Vesuvio/*Via *Stabiana* and Via *della Fortuna/*Via *di Nola* with water supply to *Casa di Caecilius Iucundus* to the east and to *Fullonica di Vesonius Primus* to the west

The use of aqueduct water in Pompeii

The water-supply system in Pompeii was built to deliver water to public baths, street fountains and to a number of private houses and workshops.

Public baths required only a small water quantity, enough to fill the storage tanks faster than the water was used in the baths. In an earlier study it was estimated that the Stabian Baths were supplied from water tower no. 4 with 0.8 l/s and the Forum Baths from water tower no. 8 with 0.2 l/s (Olsson 2020). Two smaller public baths, the Suburban Baths and the Sarno Baths, were located in the south-western part of the city. They were probably supplied from the top container of water tower no. 10 through an individual water pipe in the same way as private houses, perhaps with 0.10 l/s for each of the two baths. The Central Baths were under construction at the time of the eruption in AD 79 and the aqueduct connections are not known.

Table 8 Water quantities to *Casa di Caecilius Iucundus* and to *Fullonica di Vesonius Primus* as calculated by the author

Water tower no	2	2
Private house/workshop	*Casa di Caecilius Iucundus*	*Fullonica di Vesonius Primus*
Head	5.3 m	5.3 m
Length of pipe	55 m	46 m
Diameter of pipe—standard as external minus thickness 0.5 cm acc. to author	1.3 cm	1.3 cm
Reduced area	1.33 cm^2	1.33 cm^2
Water velocity	0.78 m/s	0.86 m/s
Water quantity	0.10 l/s	0.11 l/s

Aqueduct water for public use can be summarized as 4.2 l/s for street fountains and 1.2 l/s for public baths as shown in Appendix 3. In total 5.4 l/s were for public use.

Aqueduct water for private use was delivered to houses for fountains and sometimes for kitchens and baths.[6] In workshops water was used for the production process. Citizens also collected rainwater in reservoirs in the house for later use. It is possible that they brought aqueduct water from street fountains for consumption even if the house was supplied through a small pipe with aqueduct water for the private fountains in the house.

Citizens with a private bath in the house could also have brought water from a street fountain. Nathalie de Haan has in an earlier study investigated private baths in Pompeii (De Haan 1994). Of 30 private baths investigated by her, only 16 are mentioned in the list in Appendix 2 in the present study. The other 14 private houses must have been supplied with water brought from a street fountain, the house rainwater-saving reservoir, or a deep well. Water was of special importance in the laundries for the cleaning process. Flohr has studied the excavated laundries in Pompeii and he is of the opinion that most of the workshops were directly connected to the aqueduct water supply but that smaller laundries used alternative ways to fulfil their water needs (Flohr 2004).

Aqueduct water for private use in houses and workshops has been estimated in this study to 8.5 l/s, as shown in Appendix 3.

In a previous study it was estimated that the total incoming water quantity in the aqueduct to Pompeii was 17 l/s (Olsson 2020). The water quantity was divided in the three main water pipelines with about 11 l/s to the eastern water pipeline, about 4 l/s to the central and about 2 l/s to the western water pipeline.

In this study the water distribution to public and private users has been discussed and the estimated water quantities are summarized in Appendix 3.

The eastern water pipeline distributed 8.6 l/s, which was more than half of the total water quantity supplied to the city. It was connected to seven water towers and also to three unknown towers. This pipeline supplied 2.9 l/s of aqueduct water to 26 public street fountains, 0.8 l/s to one public bath, and 5.0 l/s to 51 private houses and workshops.

The central water pipeline distributed 2.7 l/s, which was less than a quarter of the total water quantity entering the city and was connected only to three water towers and supplied 0.6 l/s of aqueduct water to seven street fountains and 2.1 l/s to 23 private houses and workshops.

[6] Aqueduct water to private houses generally went to fountains in the house and not to the kitchen.

The western water pipeline distributed 2.5 l/s, which was less than a quarter of the incoming water quantity to the city. It was connected to four water towers and supplied 0.7 l/s of aqueduct water to nine street fountains, 0.4 l/s to three public baths and 1.4 l/s to 17 private houses and workshops.

The calculations of the water quantities in small water pipes have shown that less than half of the total incoming water quantity to the city, or 5.4 l/s, was supplied for public use in the street fountains and the public baths, and that 8.5 l/s was supplied for private use. This means that the water supply for some private users must have been considered from the beginning. It is plausible that the number of private users increased over time as familiarity with the system increased.

The total estimated incoming water quantity to the city in this study is 13.9 l/s to all public and private users. This is somewhat less than the 17 l/s estimated in the earlier study but could be explained by aqueduct water supplied to users in the not-yet excavated parts of the city.

Summary and conclusions

This study has discussed the water supply to users in small water pipes and presented a calculation method based on levels, pipe lengths, and pipe dimensions:

$$u = \sqrt{\frac{2gh}{1 + \frac{\lambda L}{D} + nk}} \tag{8}$$

The simplified calculation method could be used for the calculation of water velocity in water pipes when three geometrical variables are known, the head (h), the length of the pipe (L) and the diameter of the small pipe (D), but the method will only result in estimations. The water quantity could then be calculated as the water velocity multiplied with the area of the cross-section of the pipe.

The head and the length of the pipe to each street fountain have been calculated with some accuracy, and the distance to the entrance of houses and workshops has been estimated. Most of the water users are supplied from a water tower at a far distance. The water pipe dimensions are not known.

In this study water velocities and water quantities to public and private users have been estimated with uncertainty for the smallest size of water pipe, using figures given by Fahlbusch and interpreted by the author as external diameter with internal measurements taking into account an assumed thickness 0.5 cm for the lead plate used in the manufacturing. With the water quantities that were available in the three main water pipelines it has been shown that water could reach all water users through such small water pipes, also those at a far distance of more than 100 m, but only if the pipe dimensions were small enough. The estimations have indicated that most of the aqueduct water that reached Pompeii went to private users. Thus, it is reasonable to assume that the water-supply system was designed to accommodate private use from the beginning.

In this study calculations of water quantities resulted only in estimations. To be able to calculate water quantities in small water pipes with good accuracy in the future, it is necessary to achieve better knowledge of the dimensions of the small water pipes in Pompeii. A study of those pipes fragments kept in storerooms in the city would give us better knowledge of their measurements, even if the find-spot of the fragment is unknown. The calculations of water quantities in this study have given only very rough estimations of the real values, but the equation presented is exact and deserves use in the future as more exact values of pipe dimensions and lengths are measured on site and in the storerooms.

The significance of the conclusions in the third study

The purpose in the third study was to present a calculation method for water quantities to users to demonstrate how water was delivered to all public users, street fountains and public baths, and to all private users, houses and workshops, and which priority the system gave between public and private use.

A calculation method based on Bernoulli's equation for fluid mechanics has been presented. The water velocity in a pipe can be calculated considering only three geometrical variables, the head (h), the length of the pipe (L), and the inner diameter of the pipe (d). Most water users were located at a far distance from the water tower that supplied water to the user.

With the water quantities that were available in the three main water pipelines it has been shown that water could reach all water users through small water pipes but only if the pipe dimensions were small enough. The calculations were made for the smallest size, a 5-finger pipe as described by Frontinus/Fahlbusch but interpreted by the author as external diameter and subtracting 0.5 cm corresponding to the estimated thickness of the pipe wall to obtain the hypothetical internal diameter. Larger pipes would have emptied the system and the available water quantities could not have reached all water users.

The calculations of water quantities to the street fountains showed that the length of the pipe had a significant influence and that the water quantities to street fountains located close to a water tower were higher, on average 0.20 l/s, than to street fountains at a far distance, on average 0.06 l/s. The total water quantity supplied to all street fountains was summarized to 4.2 l/s, for public baths to 1.2 l/s and in total for public use 5.4 l/s.

Aqueduct water for private use was delivered to houses for fountains and sometimes for kitchens and baths. In workshops water was used for the production process. Most of the houses and workshops were located at a large distance from the tower it was connected to. The lengths of the pipes had a significant influence in a similar way as for street fountains and the calculations of water quantities should be seen as estimations, on average 0.11 l/s at a close distance and in average 0.06 l/s at a far distance.

The total water quantity for private use in houses and workshops was estimated to 8.5 l/s.

This means that the water supply for some private users must have been considered from the beginning.

Appendix 1: water supply to street fountains

Number	Location	Water tower no. (level at top)	Head (m)	Length (m)	Water quantity (l/s)		
					λ = 0.04	λ = 0.06	λ = 0.09
1	I 4, 15	4 (+32.1)	6.2	10	0.26	0.22	0.18
2	I 5, 2	Unknown	–	–	–	–	–
3	I 9, 1	5 (+29.7)	4.2	85	0.07	0.06	0.05
4	I 10, 1	5 (+29.7)	6.3	80	0.09	0.07	0.06
5	I 12, 2	5 (+29.7)	5.1	165	0.06	0.05	0.04
6	I 13, 10	6 (+26.5)	4.9	130	0.07	0.05	0.04
7	I 16, 4	Unknown	–	–	–	–	–
8	II 1, 2	6 (+26.5)	2.9	34	0.10	0.08	0.07
9	II 3, 5	6 (+26.5)	3.1	148	0.05	0.04	0.03
10	III 11, 1	? 14 (+36.3)	8.9	166	0.08	0.06	0.05
11	V 1, 3	2 (+39.7)	7.2	43	0.13	0.11	0.09
12	VI 1, 19	13 (+41.6)	0.9	4	0.14	0.12	0.10
13	VI 3, 20	8 (+41.7)	3.0	48	0.08	0.07	0.06
14	VI 8, 24	7 (+41.9)	4.9	118	0.07	0.06	0.05
15	A. Caligula	8 (+41.7)	5.0	64	0.09	0.08	0.06
16	VI 13, 7	7 (+41.9)	7.7	94	0.10	0.08	0.06
17	VI 13, 17	7 (+41.9)	3.8	46	0.10	0.08	0.06
18	VI 14, 17	2 (+39.7)	6.6	15	0.21	0.18	0.14
19	VI 16, 4	1 (+42.6)	7.0	10	0.27	0.22	0.19
20	VI 16, 19	1 (+42.6)	1.7	103	0.04	0.03	0.03
21	VI 16, 28	7 (+41.9)	1.0	56	0.04	0.04	0.03
22	VII 1, 32	3 (+36.2)	6.2	18	0.19	0.16	0.13
23	VII 4, 32	3 (+36.2)	2.2	150	0.04	0.03	0.03
24	VII 7, 26	8 (+41.7)	4.6	74	0.08	0.07	0.06
25	A. Forum	8 (+41.7)	3.8	100	0.07	0.05	0.04
26	VII 9, 67	? 11 (+34.7)	4.3	78	0.08	0.06	0.05
27	VII 11, 5	9 (+39.2)	7.8	51	0.13	0.11	0.09
28	VII 14, 13	4 (+32.1)	6.1	93	0.09	0.07	0.06
29	VII 15, 1	? 10 (+37.0)	2.3	92	0.05	0.04	0.04
30	VII 15, 12	? 8 (+41.7)	7.5	156	0.07	0.06	0.05
31	VIII 2, 20	10 (+37.0)	3.0	188	0.04	0.03	0.03
32	VIII 2, 29	? 11 (+34.7)	1.5	44	0.06	0.05	0.04
33	VIII 2, 11	10 (+37.0)	2.9	108	0.05	0.05	0.04
34	VIII 7, 30	? 4 (+32.1)	7.1	151	0.07	0.06	0.05
35	Tri. Forum	? 4 (32.1)	7.0	155	0.07	0.06	0.05
36	Glad. Barr	Unknown	–	–	–	–	–
37	VIII 7, 1	Unknown	–	–	–	–	–
38	VIII 7, 25	Unknown	–	–	–	–	–
39	IX 7, 17	Unknown	–	–	–	–	–
40	IX 8, 1	14 (+36.3)	3.3	110	0.06	0.05	0.04

Number	Location	Water tower no. (level at top)	Head (m)	Length (m)	Water quantity (l/s)		
					λ = 0.04	λ = 0.06	λ = 0.09
41	IX 10, 2	14 (+36.3)	4.3	16	0.16	0.14	0.11
42	IX 11, 1	5 (+29.7)	3.4	13	0.16	0.13	0.11

Appendix 2: water supply to houses and workshops

Gemma Jansen has in her thesis from 2001 identified and listed 91 houses and workshops supplied with aqueduct water as shown below (Jansen 2001).

Number	Location	House	Water tower no.	Distance (m).
REGIO I				
1	I 3, 3.4.31		4	102
2	(I 4, 5.25)	*Casa del Citarista*	4	52
3	I 4, 9.10		4	38
4	I 4, 20.21		4	58
5	(I 6, 7)	*Fullonica di Stephanus*	4	96
6	(I 7, 1.20)	*Casa di Paquius Proculus*	5	39
7	(I 7, 10–12. 19)	*Casa dell'Efebo*	5	35
8	(I 10, 4)	*Casa del Menandro*	5	139
9	I 12, 2		5	127
Total		9 houses in *Regio* I		
REGIO II				
10	(II 2,2)	*Casa di Octavius Quartio*	6	15
11	(II 4, 2–12)	*Praedia di Julia Felix*	6	107
12	II 9, 1.5.6		6	193
Total		3 houses in *Regio* II		
REGIO III				
13	(III 2,1)	*Casa di Trebius Valens*	5	133
Total		1 house in *Regio* III		
REGIO IV				
Total		No houses in *Regio* IV		
REGIO V				
14	V 1, 3		2	36
15	(V 1, 7)	*Casa del Torello di bronzo*	2	44
16	(V 1, 18.11–12)	*Casa degli Epigrammi Greci*	1	46
17	(V 1, 22–27.10)	*Casa di Caecilius Iucundus*	2	55
18	V 2, 4 i		1	36
19	(V 2, 4)	*Casa delle Nozze d'Argento*	1	52
20	V 3, 11		14	145
21	V 4, 1.2		14	77
Total		8 houses in *Regio* V		

Number	Location	House	Water tower no.	Distance (m)
REGIO VI				
22	VI 1, 5–8		13	73
23	(VI 2, 4)	*Casa di Sallustius*	13	33
24	(VI 6, 1)	*Casa di Pansa*	8	23
25	VI 7, 18		7	189
26	(VI 7, 23)	*Casa di Apollo*	7	241
27	VI 8, 20.21.2		8	123
28	(VI 8, 22)	*Casa della Fontana Grande*	7	155
29	(VI 8, 23)	*Casa della Fontana Piccola*	7	145
30	(VI 9, 2)	*Casa di Maleagro*	7	205
31	VI 9, 3–5.10.12		7	185
32	(VI 9, ?)	*Casa dei Dioscuri*	7	157
33	VI 10, 6.17		7	145
34	(VI 10, ?)	*Casa dell'Ancora*	8	113
35	(VI 11, 8–10)	*Casa del Labirinto*	7	145
36	(VI 12, 17)	*Casa del Fauno*	8	115
37	(VI 14, 4.43)	*Casa degli Scienziati*	2	78
38	(VI 14, 18–20)	*Casa di Orfeo / Vesonius Primus*	2	22
39	(VI 14, 22)	*Fullonica di Vesonius Primus*	2	46
40	VI 14, 28–32		1	27
41	(VI 15, 1.27)	*Casa dei Vettii*	7	25
42	VI 15, 2.26		7	45
43	VI 15, 5.24.25		7	77
44	(VI 16, 6.7.38)	*Casa degli Amorini Dorati*	1	31
45	VI 17, 42–44		13	111
Total		24 houses in *Regio* VI		

Number	Location	House	Water tower no.	Distance (m)
REGIO VII				
46	(VII 1, 25.46.47)	*Casa di Vedius Siricus*	3	46
47	(VII 2, 16)	*Casa di M. Gavius Rufus*	3	106
48	VII 2, 18.19.42		3	116
49	VII 2, 20.21.41		3	134
50	(VII 2, 45)	*Casa dell'Orso*	3	70
51	VII 2, 48.49		3	56
52	VII 3, 1–3.38–40		2	82
53	VII 3, 24.25		3	100
54	(VII 4, ?)	*Casa dei Capitelli Colorati*	8	147
55	(VII 4, ?)	*Casa della Fontana*	8	177
56	(VII 4, ?)	*Casa dei Capitelli Figurati*	8	179
57	VII 4, 58.59		8	139
58	VII 4, 60–63.8		8	111
59	VII 9, 40.41.27		9	26
60	VII 9, 47.48.51.65		9	42
61	VII 10, 3.14		9	36

Number	Location	House	Water tower no.	Distance (m)
62	VII 10, 9–12		9	46
63	VII 12, 3		9	72
64	VII 12, 11		9	128
65	VII 12, 22–23		9	70
66	VII 12, 28		9	38
67	VII 13, 8.14		11	106
68	(VII 15, 2)	*Casa del Marinaio*	10	74
69	VII 15, 12		8	135
70	(VII 16, 17)	*Villa di M. Fabius Rufus*	10	74
Total		25 houses in *Regio* VII		

Number	Location	House	Water tower no.	Distance (m)
REGIO VIII				
71	(VIII 2, 21)	*Casa con Ninfeo*	10	208
72	VIII 3, 14.15		10	236
73	(VIII 4,4)	*Casa di Holconius Rufus*	11	190
74	VIII 4, 12		4	46
75	VIII 4, 14–16.22.23.30		4	42
76	VIII 5, 28		11	166
Total		6 houses in *Regio* VIII		
REGIO IX				
77	(IX 1, 20)	*Casa dei Diadumeni*	4	42
78	IX 1, 22.29		4	54
79	IX 2, 7.8		3	54
80	(IX 3, 5–24)	*Casa di Marcus Lucretius*	3	42
81	IX 3, 19.20		3	74
82	IX 5, 7–9.15		14	145
83	IX 5, 11.13		14	133
84	IX 5, 18–21		3	146
85	IX 6, 4–7		3	76
86	IX 7, 16		3	146
87	(IX 7, ?)	*Casa dello Speccio*	4	86
88	IX 7, 24.25		4	116
89	(IX 8, 3–6)	*Casa del Centenario*	14	105
90	(IX 10, 2)	*Casa di Obellius Firmus*	14	15
91	(IX 14, ?)	*Villa di Diomede*	14	35
Total		15 houses in *Regio* IX		

Appendix 3: water supply for public and private use

The eastern water pipeline

Water tower no.	To street fountain no.	To public baths	To private houses and workshops no.	Estimated water quantity
1	19, 20		16, 18, 19, 40, 44	
2	11, 18		14, 15, 17, 37, 38, 39, 52	
3	22, 23		46, 47, 48, 49, 50, 51, 53, 79, 80, 81, 84, 85, 86	
4	1, 28, 34, 35	Stabian Baths	1, 2, 3, 4, 5, 74, 75, 77, 78, 87, 88	
5	3, 4, 5, 42		6, 7, 8, 9, 13	
6	6, 8, 9		10, 11, 12	
14	10, 40, 41		20, 21, 82, 83, 89, 90, 91	
Three unknown	2, 7, 36, 37, 38, 39			
Total 7 + 3 towers	26 fountains 2.9 l/s	1 bath 0.8 l/s	51 houses 5.0 l/s	8.6 (11) l/s

The central water pipeline

Water tower no.	To street fountain no.	To public baths	To private houses and workshops no.	Estimated water quantity
7	14, 16, 17, 21		25, 26, 28, 29, 30, 31, 32, 33, 35, 41, 42, 43	
9	27		59, 60, 61, 62, 63, 64, 65, 66	
11	26, 32		67, 73, 76	
Total 3 towers	7 fountains 0.6 l/s	No bath 0	23 houses 2.1 l/s	2.7 (4) l/s

The western water pipeline

Water tower no.	To street fountain no.	To public baths	To private houses and workshops no.	Estimated water quantity
12				
13	12		22, 23, 45	
8	13, 15, 24, 25, 30	Forum Baths	24, 27, 34, 36, 54, 55, 56, 57, 58, 69	
10	29, 31, 33	Suburban Baths Sarno Baths	68, 70, 71, 72	
Total 4 towers	9 fountains 0.7 l/s	3 baths 0.4 l/s	17 houses 1.4 l/s	2.5 (2) l/s
Total	4.2 l/s	1.2 l/s	8.5 l/s	13.9 (17) l/s

Funding Open access funding provided by Lund University.

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