J. Riley Snyder

Exploiting the Landscape: Quantifying the Material Resources Used in the Construction of the Long-distance Water Supply of Constantinople

For the new eastern capital city of Constantinople to meet the needs of its growing populace in the 4th century, the urban infrastructure was bolstered by large projects, many rivalling the scale and intricacy of those undertaken during the height of Imperial Rome. A prime example of this is the extensive channel network of the 4th and 5th centuries, built in the hinterland of Constantinople to supply fresh water to the city from springs hundreds of kilometres away (**fig. 1**). Important questions pertaining to construction organisation derive from the fact that, within these two centuries, Constantinople was provided the necessary infrastructure of a booming metropolis, including the completion of the longest water supply system of the Roman World.

What were the material requirements for constructing such a long water supply system? How do these requirements compare to other structures in the ancient and modern world? In what ways did these material requirements both affect and rely upon the environment in which it was built? The aim of this paper is to answer some of the questions surrounding the scale of the long-distance Water Supply of Constantinople. Through a volumetric examination of the structures and by material differentiation and quantification, the resulting data will be used to relate the construction of this system to its reliance on the local and regional landscapes.

This study combines many resources such as topographical data of the Thracian Peninsula, structural measurements taken by the Anastasian Wall Project[1], image analysis of architectural elements, and the development of formulas to calculate the volume of water supply. The resulting data is then used to dissect these systems into their individual material building blocks and further, into the raw materials and fuel used in the production of composite materials.

Looking solely at the distance that these water channels traversed across the countryside, we get an interesting comparative figure for other long-distance aqueducts of the ancient world. As will be discussed below, this comparison confirms that, in order to sustain its population, the Water Supply of Constantinople stretched much further into the hinterland than that of any other water supply in the ancient world. While a measure of distance tells of the successes of a highly organised administration and workforce as well as the city's great investment in distant natural water sources, so much more can be derived from the structure itself.

History

Constantinople was poorly situated for natural fresh water sources such as wells, springs and streams creating a need for water from the hinterland[2]. According to Pliny the Younger, Hadrian provided an aqueduct for Nicaea in 123[3]. It was likely that he did the same for Byzantium on his trip to Bithynia and Thrace[4].

The city of Constantinople was growing in population and prosperity after its dedication in 330 and the quantity of water provided by the aqueduct of Hadrian proved insufficient[5]. To remedy this problem, a long-distance water supply was initiated, likely by Constantius II, in the mid-4th century and inaugurated by Valens in 373[6]. Soon after, sometime in the early 5th century, there was a second phase of construction of this long-distance water supply that extended much further west[7].

The 4th-century phase of the Water Supply of Constantinople sourced water from two major springs. The first was from springs around Danamandıra (İl İstanbul/TR) and the second was the supplementary channel closer to Constantinople near the modern village of Pınarca (İl İstanbul), both being narrow channels averaging a width of 0.7 m (**fig. 2**). The addition of the 5th-century line saw the extension of the water supply to Vize (Pazarlı Spring, İl Kırklareli/TR). At this source, the channel was narrow like the 4th-century channel.

---

[1] The major source of data on which this paper bases most of its estimates comes from the surveys undertaken between 2000 and 2009 by the Anastasian Wall Project, led by James Crow: Crow/Bardill/Bayliss, Water Supply. – Crow/Maktav, Survey. – Crow, Ruling the Waters. – Crow, History of Water. – Recent research (see Ruggeri et al., GIS-based assessment) on the engineering of Constantinople's water supply has produced new information on the location and route of channels in the hinterland. Based on GIS and hydrological analysis, it is probable that the total length of the system was much longer than what is presented in this paper.

[2] Mango, Water Supply 9. – Crow, Ruling the Waters 52-53.

[3] Plin. Epist. 10, 37-38.

[4] Mango, Water Supply 10. – Crow/Bardill/Bayliss, Water Supply 13.

[5] Mango, Water Supply 12. – Crow/Bardill/Bayliss, Water Supply 9.

[6] Crow/Ricci, Interim Report 237. – Crow, Infrastructure 270.

[7] Crow, Infrastructure 272.

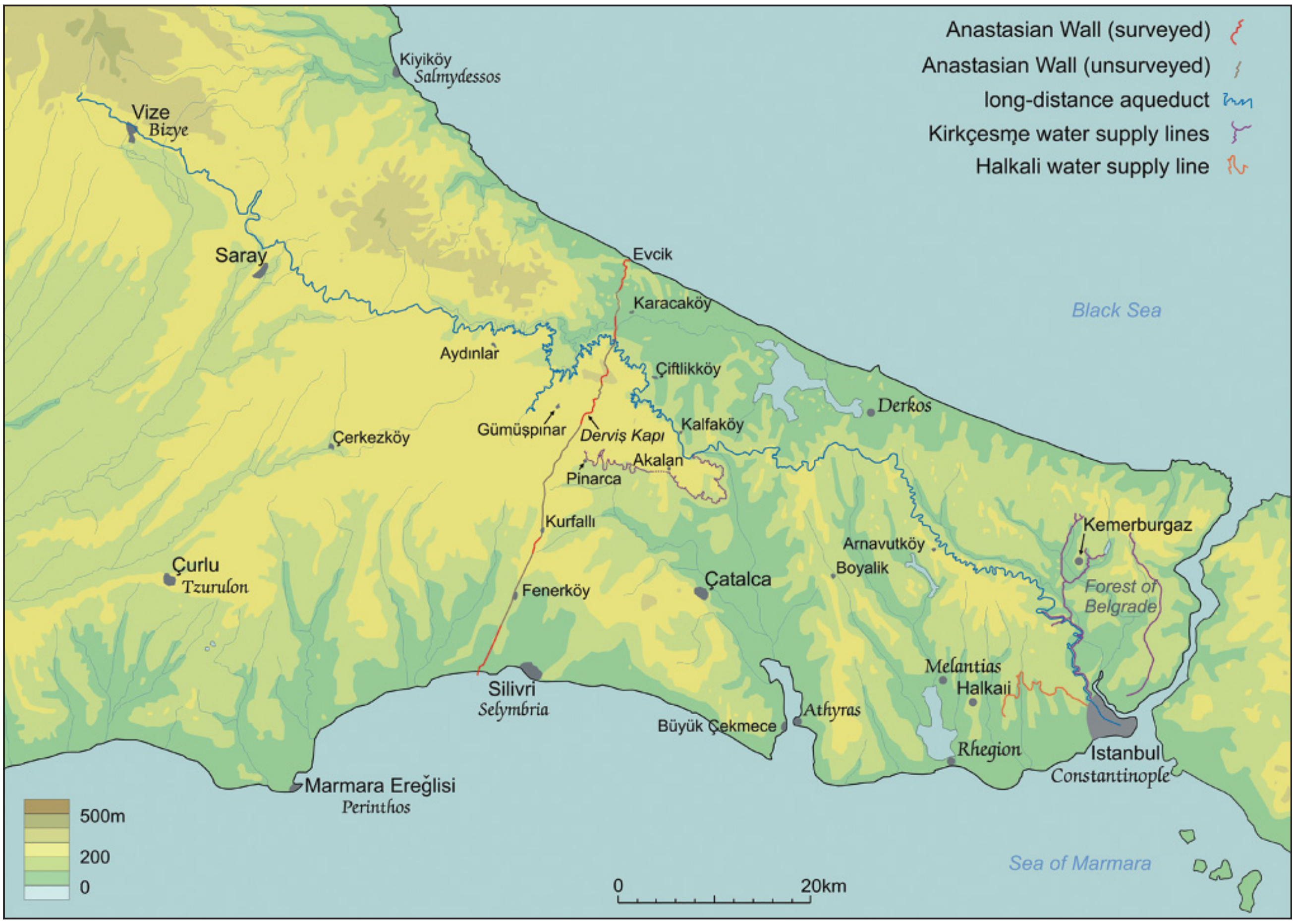

Fig. 1 Map of the Water Supply of Constantinople and Anastasian Wall in Thrace. – (After Crow/Bardill/Bayliss, Water Supply 11 fig. 2.1).

As this line approached the precursory 4th-century lines, the channel became much wider, averaging 1.5 m. It continued running mostly parallel (although at a higher elevation) until the two channels merged somewhere near Kalfaköy (İl İstanbul). Over the section where the channels of the two phases ran parallel, many new monumental bridges, such as Kurşunlugerme (**fig. 3**) and Büyükgerme (both İl İstanbul) were built to accommodate the terrain.

Other than a period of partial disruption lasting 150 years from the early 7th century on, the system flowed well into the late 12th century. This period of disruption should not be understated, as it would have limited the water supply to the lower parts of the city. The fear of insufficient water flow to the city seems to be a common theme in the histories of Constantinople and the maintenance required for such a long and intricate system eventually proved too much to keep it running[8].

Landscapes, Building Methods, and Materials

The entirety of water supply of Constantinople covers a distance, as the crow flies, of almost 120 km from the Theodosian Land Walls to the westernmost spring outside of the modern Turkish town of Vize (Bizye). Over this distance, the landscape changes from rolling open lowlands to densely forested and mountainous uplands. Not surprisingly, the greatest concentration of aqueduct bridges is found in the latter, between the villages of Çiftlikköy and Binkılıç (both İl İstanbul). The steep hills and deep valleys of this region also host the largest of the aqueduct bridges (**fig. 4**) in the hinterland with dimensions up to 175 m long and 37 m high.

The modern survival of the water supply system is heavily reliant on the terrain in which they are located. In recent decades, the massive urban expansion of Istanbul has greatly hindered the possibility of locating the physical remains of the water supply closer to the modern city. Further northwest, in the region of Catalca (İl İstanbul), the dense forests of oak and beech cloak from view even the largest bridges. As little development has taken place in this region and the population density is low, the modern landscape is likely very similar to that of the past[9].

The long distance water supply of the 4th and 5th centuries is made up of two primary structural elements: bridges and channels. The majority of the channel is built and buried im-

---

[8] Crow, Ruling the Waters 52-53.

[9] Meiggs, Trees and Timber 393.

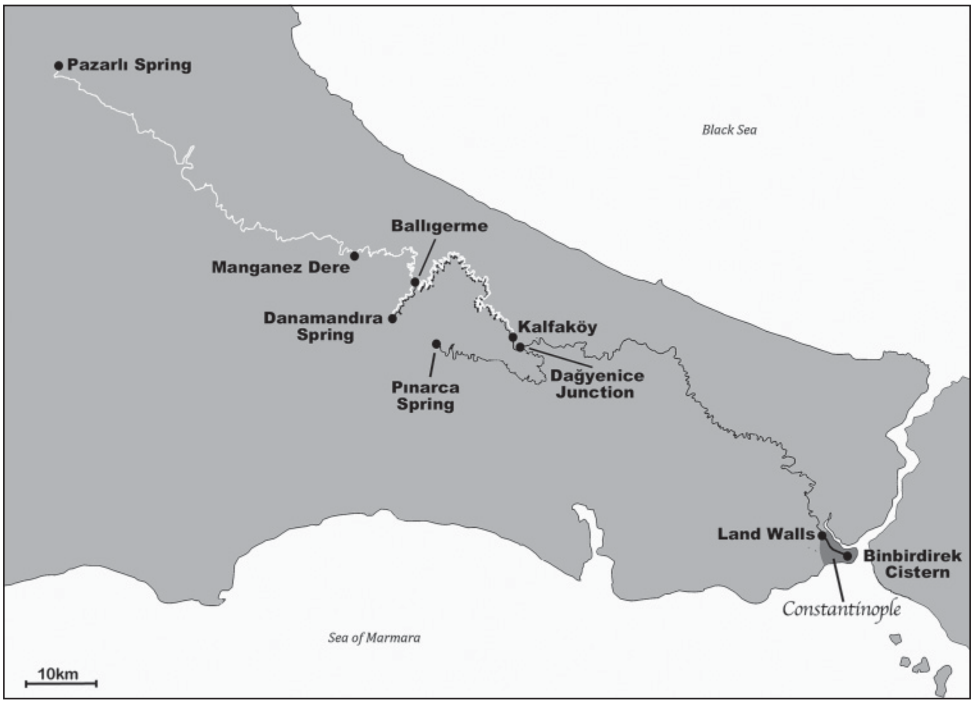

Fig. 2 Map of Thrace indicating the locations where the lines of the Water Supply of Constantinople are divided. The black line represents the 4th-century phase of construction and the white represents the 5th-century phase. – (Illustration R. Snyder).

Fig. 3 5th-century aqueduct bridge of Kurşunlugerme. – (Photo R. Snyder).

mediately below ground in the »cut and cover« method, with regular intervals of inspection shafts for maintenance access. The course of the channel occasionally runs through rock-cut tunnels[10] as well as over earthen embankments[11].

The walls and channel floors of the narrow and wide channels are made of small squared blocks or rubble stone set in hard pink mortar (**fig. 5**). The walls and flooring of the wide channel average 1.5 m thick while the narrow channel average 0.65 m. The vaulting of the wide channel is typically a shallow curve, also made of squared blocks or rubble. The narrow channel has a greater variety of vaulting such as steep or shallow segmental arches or pedimented vaults, all of which are built with rubble stone. The difference in vault construction has not been linked to specific building pha-

---

[10] Crow/Bardill/Bayliss, Water Supply 46. 108.

[11] Crow/Maktav, Survey 54-55. – Maktav et al., Remote Sensing 1669-1670.

Fig. 4 5th-century aqueduct bridge of Kumarlıdere. – (Photo R. Snyder).

Fig. 5 Small section of intact channel near Binkılıc showing arched limestone vaulting and channel lining mortar of the channel walls and floor. – (Photo J. Crow).

ses[12] and is most likely based on the availability of construction materials over varying local bedrock. This is not surprising as the bedrock geology of the Thracian Peninsula varies considerably between marine and crystalline limestone deposits as well as pockets of undifferentiated metamorphosed facies of micaschist, quartzite, gneiss and metagranite[13].

In the 4th- and 5th-century phases, aqueduct bridges were constructed with a mortared rubble core faced with limestone blocks fastened by iron clamps sealed in lead. In the 4th century, bridges were typically faced with rusticated limestone blocks and timber cribwork to strengthen the core while the mortar set and settled[14]. On average, bridges of the 5th cen-

---

[12] Crow/Bardill/Bayliss, Water Supply 107.
[13] Bono/Crow/Bayliss, Water Supply 1329-1330.
[14] Crow/Bardill/Bayliss, Water Supply 103.

Fig. 6 Metamorphosed limestone facing stone with mason's mark from the 5th-century aqueduct bridge of Kumarlıdere. – (Photo R. Snyder).

tury were larger in order to accommodate the wider channel and capacious valleys. The greatest of these bridges, referred to as »monumental bridges«,[15] are faced with large metamorphosed limestone blocks. These blocks are commonly quarry-dressed with drafted margins, many bearing mason's marks (**fig. 6**). While the longest and widest of these bridges, Kurşunlugerme, is buttressed, this is an exceptional feature for the 4th- and 5th-century construction phases.

In the construction of aqueduct bridges, rubble stone used in the core of the structures seems to be made of the same (or similar) stone materials to the facing stones. The best evidence for this comes from 5th-century monumental bridges like Kurşunlugerme and Kumarlıdere (İl İstanbul) where the facing stones have sheered off (**fig. 7**), most likely due to seismic events, to reveal the core of rubble stone and hard pink mortar.

A unique aspect of the architecture of the long-distance water supply is that brick was not used as a load-bearing structural feature. The common construction technique of late-antique Constantinopolitan large-scale architecture was alternating stone courses with brick bonding courses, such as the original church of Hagia Sophia, Theodosian Land Walls, the Hippodrome, and even the Aqueduct of Valens[16]. The 4th- and 5th-century phases of the long distance water supply in the hinterland were solely constructed in stone and mortar. However, large quantities of crushed bricks were used as aggregate and in the structural and channel-lining mortars.

Fig. 7 5th century aqueduct bridge of Kumarlıdere with exposed mortar and rubble core. – (Photo R. Snyder).

---

[15] Crow/Bardill/Bayliss, Water Supply 103.

[16] Ward-Perkins, Building Methods. – Krautheimer, Byzantine Architecture 79-80.

Channel Section	Channel Width (m)	Number of Bridges	Length (km)
Danamandıra to Constantinople	0.70	30	227.24
Pınarca to junction near Dağyenice	0.60	5	40.64
Land Walls to Binbirdirek Cistern	0.70	1	3.35

Tab. 1 Features of channel sections from the 4th-century phase.

Unlike the stone used in the construction of the long-distance water supply, the brick aggregate in the mortar was not produced locally. In a recent study of the mortars, X-Ray Diffraction Analysis has indicated that the brick material from the water supply comes from a single source, similar to the bricks produced for the major building projects within Constantinople[17]. This is not surprising, as Constantinople would have had a thriving brick industry in the 4th and 5th centuries, probably located not far from the Theodosian Land walls[18]. Similarly, it can be assumed that the processing and manufacture of iron clamps would have taken place in close proximity to the capital city and not produced onsite.

Length

The length of the long distance water supply is a good starting point for understanding the scale of the construction project. However, in order to progress towards a better understanding of the construction material requirements, this overall figure needs to be broken down into smaller divisions based on building phase and channel dimensions.

The first of these divisions was between the 4th-century building phase and the 5th-century extension. While these two systems were built separately, they eventually formed one unified channel as it approached the city. However, until this point, water had travelled in two separate channels in order to maintain the proper gradient for optimal flow. The second division was made based on the width of the channel, which stays consistent in the 4th century but considerably increases in a large portion of the 5th-century channel. This second division also took into account the junction channel sections as well as where the channel crossed the city's land walls (see **fig. 2**).

4th-century phase of the water supply

In the 4th century, the first phase of the long distance supply system was made up of over 271 km of channels, bridges, and tunnels (**tab. 1**). For comparison, if all of the lines of this phase were pulled into a straight line, it would stretch from the Trafalgar Square in London to York Minster in York. This is almost three times longer than Rome's longest aqueduct – the 91 km-long Aqua Marcia[19] – and over 100 km longer than Jordan's Gadara Aqueduct[20]. Over the distance of the 4th-century lines, 36 bridges were built to carry the water over the varying terrain of Constantinople's hinterland, including the famous Aqueduct of Valens (Bozdoğan Kemeri, İl İstanbul). In this original phase of construction, the channel maintains a uniform width of around 0.70 m.

5th-Century Phase of the water upply

Compared to the 36 bridges from the 4th-century phase credited to Valens, the 5th-century water supply required 52 new locations for aqueduct bridges and 16 4th-century bridges to be rebuilt (**tab. 2**). However, the 5th-century addition is much shorter than the 4th-century line, stretching 183 km. This is still twice as long at the Aqua Marcia and around 13 km longer than the Gadara Aqueduct. With this 88 km difference between the two phases of the long-distance Constantinopolitan water supply system, it is difficult to keep from categorising this addition as »smaller«. As we will see in the next section on volume estimates, it can be deceiving to base the construction requirements of these structures solely on their length.

Taking into consideration all of the channels that provided water to the city of Constantinople – the 271 km-long 4th-century system, the 183 km addition of the 5th-century, and the 47 km-long 2nd-century Hadrianic aqueduct[21] – the total distance of functioning channels in the 5th century reached 501 km. This distance, just one kilometre shorter

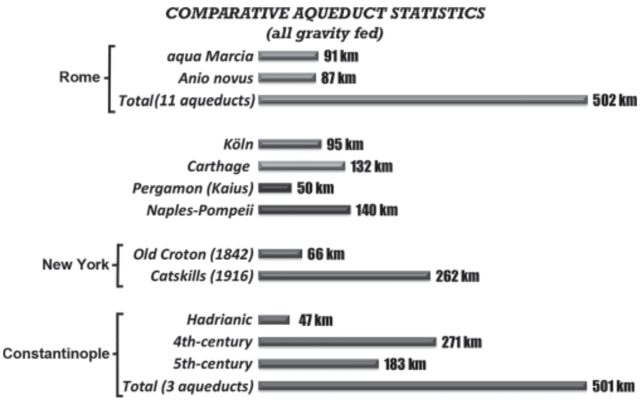

Fig. 8 Comparative chart of the lengths of gravity-fed water supply systems from antiquity and recent history. – (Illustration R. Snyder).

---

[17] Snyder, Construction Requirements 182-184.

[18] Bardill, Brickstamps 3-4. – Ousterhout, Master Builders 128.

[19] Hodge, Aqueducts 347.

[20] Döring, Gadara.

[21] See Chapter 3 of Crow/Bardill/Bayliss, Water Supply.

Tab. 2 Features of channel sections from the 5th-century phase.

Channel Section	Channel Width (m)	Number of Bridges	Length (km)
Pazarlı to Manganez Dere (K9)	0.70	13	51.19
Manganez Dere (K9) to Ballıgerme (K18)	1.60	13	80.26
Ballıgerme (K18) to Kalfaköy	1.50	31	51.26

than the total length of all eleven aqueducts of Rome (**fig. 8**), was built in only three phases. Furthermore, both the 4th- and 5th-century phases are far longer than any of the individual aqueducts of Rome. As discussed earlier, this entire system would be functional until the 12th century – with occasions of long disruption, however. While this study does not take maintenance and upkeep into consideration, it should be noted that this great distance would require constant attention – sometimes even a massive labour force to repair and rebuild[22].

The separate Hadrianic system was still in use through the Early Ottoman times and should not be discounted from the overall discussion of the city's water supply. However, this study deals with the construction of the long-distance water supply of the 4th and 5th centuries. Thus, we will be using a total distance figure of 454 km in the following discussion.

Structural Volume

Having established the total distances of the 4th- and 5th-century water supply lines, it is now possible to estimate the total volume of the structures that make up the system. Before beginning a detailed discussion, it should be clearly noted that all figures used are estimates, and to a greater or lesser degree, hypothetical. While to my knowledge, all formulae, measurements, and calculations accurately reflect the original sources and integrity of their scholarship, any miscalculations, inconsistencies or omissions found in this chapter are the sole responsibility of the author.

There are two types of structures that will be calculated independently: aqueduct bridges and channels. The most intricate part of these calculations comes from the numerous bridges that play a very significant role in the success of bringing water to the city of Constantinople. However, as we will see, the greatest extent of the water supply – in terms of length and structural volume – are the long stretches of buried channels. It should be noted that even though there are instances where channels run through rock-cut tunnels and over earthen embankments, both of these alternatives to the »cut and cover« construction still include channels built of stone masonry. Thus, tunnels and embankments would have no influence on volumetric estimates.

Aqueduct Bridges

Since there are no set standards for the size of aqueduct bridges due to their function as elevated spans across natural terrain, it would be impossible to choose a single aqueduct bridge as an average representation for the whole system. Fortunately, extensive data obtained through surveys of the water supply facilitated the calculations of many of the bridges[23]. Topographical data of the water supply lines, as well as comparative analysis of similar bridges also proved advantageous for estimating bridges that are no longer in existence or ruined bridges that yielded insufficient data.

There are seven main variables used to measure these bridges: width of the bridge, height of the bridge, length of the bridge at the top, length of the bridge at the base, arch height of the tier, arch width of the tier, and number of arches of the tier. While a survey from the 1930s provides the primary source of measurements for the Aqueduct of Valens[24], recent archaeological work has produced the most comprehensive collection of measurements for the bridges outside the land walls[25].

The 4th-century network of the water supply had a total of 36 bridges over its full length of 271 km. All of these bridges, including the largest bridge, the so-called Aqueduct of Valens, are combined for a total structural volume of over 115 000 m³. Interestingly, 67 % of this is made up of the Aqueduct of Valens, which was estimated to be almost 78 000 m³. Without including this massive aqueduct bridge, the average structural volume for the 4th-century bridges of the hinterland is a little over 1000 m³.

For the 5th-century water supply, the three sections contain 57 new bridges and 11 others built to replace 4th-century bridges. These 68 bridges add up to almost 300 000 m³ of structural volume. The combination of channels spanning more valleys, the large scale of the monumental bridges, and bridges built to replace some on the 4th-century line makes the total structure volume of the 5th-century extension almost three times greater than that of the 4th century. Averaging 4400 m³ per bridge, the 5th-century phase quite clearly illustrates that, despite the shorter length, the construction project would test the capabilities of Late Antique architects and masons as much (or more) than the 4th-century phase.

---

[22] Ousterhout, Master Builders 129. – Crow, Ruling the Waters 46-51.

[23] Crow/Bardill/Bayliss, Water Supply.

[24] Dalman/Wittek, Valens-Aquädukt.

[25] Çeçen, Water Supply Line. – Crow/Bardill/Bayliss, Water Supply.

Channels – 4th Century

The three channel sections of the 4th-century system remain largely similar in dimensions over their length. The sections of Danamandira to Constantinople and Land Walls to Binbirdirek Cistern have a comparable height of the opening (1.55 m), width of the opening (0.70 m), wall thicknesses (0.70 m), and vault thickness (0.30 m), yielding a cross-sectional area of 3.46 m². The third section from Pınarca to the junction near Dağyenice (İl İstanbul) has the smaller cross-sectional area, averaging only 2.63 m². This can be attributed to the narrowest width of 0.6 m and height of 1.3 m of the channel opening.

The total structural volume for the longest section of the 4th century, from Danamandira to Constantinople, was 787 000 m³. From Pınarca to the junction near Dağyenice – the second longest section but with the smallest surface area – measures 107 000 m³. Finally, the short stretch from the Theodosian Land Walls of Constantinople to Binbirdirek Cistern has an estimated structural volume of 12 000 m³. It should be noted that the only surviving evidence for the 4th-century channel within the city walls is from the Aqueduct of Valens[26].

Channels – 5th Century

Due to the changes in channel dimensions of the channels over its length, each section of the 5th-century phase of the long-distance line of the water supply will be discussed separately.

Pazarlı Spring to Manganez Dere (İl İstanbul, K9[27]): The narrow channel averages 0.68 m wide and 1.4 m high. These figures only reflect the channel opening and not the channel structure. Here, the thickness of the vaulting averages 0.3 m, the side walls are around 0.65 m and the base around 0.7 m. The cross-sectional area of the channel structure was calculated at 3.02 m², making the total structural volume of this section of narrow channel over 154 000 m³.

Manganez Dere (K9) to Balligerme (İl İstanbul, K18): This stretch of channel is the longest of the 5th century and is the first section of broad channel. The channel opening averages 2.1 m high and a width over two times that of the narrow channel at 1.6 m. This larger channel area required increased structural stability and the thickness of the walls and base were increased to around 1.5 m, while the vaults became thicker at 0.7 m. This significantly increased the cross-sectional area from 3.02 m² in the previous narrow section of channel to 12.77 m². Over its distance, the structural volume was calculated to be an astounding 1 024 000 m³ – by far the most significant portion of the total structural volume figure for the entirety of Constantinople's water supply.

Ballıgerme (K18) to Kalfaköy: The final section of channels, running predominantly parallel to part of the 4th-century phase, was also broad channel. It was of similar dimensions to the stretch from Manganez Dere to Balligerme, with an average width of the opening of 1.5 m and a height of 2 m. The thickness of the channel walls, base, and vault all averaged the same as the previous section, giving a cross-sectional area of 12.32 m². The total structural volume of this stretch of channel was calculated at over 631 000 m³. Having almost the exact total length as the channel section from Pazarlı to Manganez Dere yet having a significantly larger cross sectional area produces a structural volume for this channel that is more than four times larger.

Quantifying Primary Building Materials

The term »primary building materials« is used here to designate prepared elements that are put in place to form the structure of the water supply. This is in contrast to the raw building materials needed to create these prepared elements, which will be addressed later. These primary building materials include channel-lining mortar (which has already been calculated), structural mortar, dressed facing stones, rough structural stone, and iron / lead clamps. This section will look at the quantities of these primary building materials by deconstructing the structural volumes discussed in the previous section. However, this deconstruction should not be viewed as the breakdown of a singular volumetric figure. Instead, just like examining the individual structural elements to obtain structural volume, the total estimation of materials is based on the sum of individually dissected channel sections and bridges.

As mentioned earlier, the types of rock used to construct the different structural elements of the water supply differ depending on factors such as local bedrock (for channel masonry) or phase of construction (5th-century versus 4th-century bridges). This differentiation has a significant impact on the manpower associated with ease of quarrying and transportation due to differences in hardness and weight respectively. However, a discussion of material quantities does not require a separate discussion of each type of stone. Thus, the only distinction that will be made is the difference between shaped facing stone and rubble stone.

---

[26] The length of the channel, with the exception of this aqueduct, is based on the course plotted by the Anastasian Wall Project, Crow / Bardill / Bayliss, Water Supply 110-115.

[27] These K-numbers make reference to the system used by Çeçen (Water Supply Line) and extended by Crow / Bardill / Bayliss (Water Supply) to number bridges of the water supply of Constantinople.

Aqueduct Bridges

Facing Stone

To estimate the volume of facing stones for each bridge, a calculation of the above-ground surface area was needed in order to strip the volume of facing away from the core of the bridges. This was done by multiplying the average depth of the facing by the surface area of each bridge. The dimensions of an average block used in these systems were found to be roughly 0.40 m by 0.40 m by 0.65 m. Thus, the average thickness of the facing was chosen to be 0.40 m.

For all of the bridges of the 4th-century phase, the above-ground surface area was calculated at 84 000 m². This equates to almost 34 000 m³ of facing stone volume. The volume of a single dressed facing stone of average size was 0.10 m³, meaning roughly 339 000 facing stones were necessary to construct all of the bridges of the 4th century.

The bridges of the 5th-century phase of the water supply had an estimated total above-ground surface area of over 166 000 m². This translates to almost 67 000 m³ of total volume of facing stones or roughly 666 000 facing stones of average size. This is almost twice as much facing stone as was needed by the construction of the 4th-century line.

Iron Clamps

Now that the quantity of facing stones have been estimated, we can make an inference about the total quantity of iron clamps were needed to hold them together, under the assumption that iron clamps were used at each bridge. These would be sealed in the socket with lead, which would significantly add to the cost of construction. Interestingly, the name of one of the monumental 5th-century aqueduct bridges, Kurşunlugerme, means »the leaded span«, referencing the clamps and lead settings recovered during later robbing[28]. For these purposes, lead has not been included in these calculations due to its comparatively small quantity. However, it should not be discounted in an overall discussion of manpower and cost.

It is estimated that each stone would have one entire iron clamp, with the exception of the vaulting stones. A clamp socket from the bridge Cineviz Dere[29] has been estimated to have a volume of roughly 720 cm³. In total, 305 000 iron clamps, requiring 220 m³ of iron, held the 4th-century facing blocks together. The 5th-century bridges would have needed a little over 610 000 clamps, necessitating 440 m³ of iron.

Core and Foundation Materials

Removing the volume of facing stone from the structural volume of each bridge leaves the volume of the core and foundation. This consisted of the foundation materials and the mortar and rubble core, which for the purposes of this calculation, are assumed to be similar in construction based on the similarly constructed 6th-century Anastasian Wall[30]. The entire core and foundation volume of the 4th-century phase was 82 000 m³ while the 5th-century phase was 233 000 m³.

Fig. 9 Photograph of exposed mortar and rubble core from the 5th-century bridge of Kumarlıdere. – (Photo R. Snyder).

Using image analysis software to evaluate five photographs of exposed core from various bridges of the 4th- and 5th-century phases of the water supply (**fig. 9**), the core and foundation volume was broken down into a ratio two main components: rubble stone and mortar. Surprisingly, the standard deviation between all five photographs was only 3.12 %, making the average mortar-stone ratio 1:1.75. From this ratio, the total amount of mortar used in the core of 4th-century bridges was estimated to be 30 000 m³, while rubble stone made up 52 000 m³ of the core volume. The total volumes of mortar and stone rubble from the 5th-century bridges were estimated at over 85 000 m³ and 148 000 m³ respectively.

Channels

Having no dressed facing stones, and thus no clamps, the only primary construction materials used in the building of the channels of the long-distance phase of the Water Supply of Constantinople were rubble stone, structural mortar, and channel lining mortar. Using the same methods to determine the volume of materials in the core and foundation of the aqueduct bridges, the masonry of the channels were found to have a similar mortar-stone ratio of 1:1.75.

The total structural volume of masonry of the 4th-century channels was broken down to yield almost 332 000 m³ of mortar and 573 000 m³ of rough structural stone. The entirety of the 5th-century channels of the Water Supply of Constantinople would have required 1.15 million m³ of rubble stone and more than 664 000 m³ of structural mortar.

---

[28] Crow / Bardill / Bayliss, Water Supply 58.

[29] Crow / Bardill / Bayliss, Water Supply 46.

[30] Personal comm. J. Crow.

Fig. 10 Channel lining mortar in situ showing multiple events of re-plastering. – (Photo R. Snyder).

Channel-lining Mortar

There is one additional material used in the construction of both phases of the long-distance water supply that needs to be taken into consideration. All lines of the system, including channels and aqueduct bridges, were plastered with a thin layer of fine waterproof mortar. This was one of the most crucial elements in engineering a hydrological system, as this lining would maintain a smooth surface to cut down on water turbulence[31].

A 1.5 cm layer of channel-lining mortar was applied to the flooring of the channel and up the walls to the springing of the vaults (**fig. 10**). The average cross-sectional area for the narrow channels was calculated to be around 0.03 m² while the wide channels were around 0.06 m². It turns out that the total volume of channel-lining mortar needed for the 4th- and 5th-century channels was 9000 m³ each.

As this is not a load-bearing structural element like the stone, mortar, and clamps that have just been discussed, channel-lining mortar has not yet been included in the total structural volume figures. While the required volume is miniscule compared to the total structural volume of these structures (similar to the volume of iron for the clamps), as we will see in the next section, this small figure is important when looking at the requirements of manufacture.

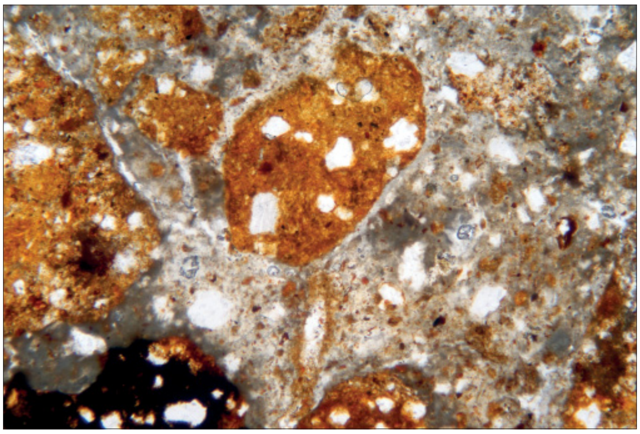

Fig. 11 Thin section micrograph of structural mortar from the 5th-century aqueduct bridge of Büyük Germe. – Scale of micrograph is roughly 1 mm × 1.5 mm. – (Photo R. Snyder).

Quantifying Raw Materials of Mortar

Mortar was arguably the most important material in the lasting success of the water supply system and as previously shown, massive quantities were needed to complete the 4th- and 5th-century systems. To understand the nature of this crucial material, samples were collected from a variety of locations of the 5th-century water supply system and examined macroscopically, microscopically, and chemically[32].

Petrographic analysis of 26 thin-sectioned mortar samples was carried out to identify and quantify the raw material components (**fig. 11**). This analysis showed that there were three main components: lime, brick (both small aggregate and powdered), and silica sand. Surprisingly there were almost no additional inclusions found except for the sample from Kurşunlugerme, which utilised small river pebbles as aggregate. No samples were examined from the 4th-century phase, but macroscopic examination of features at Pınarca Spring or the aqueduct bridge at Kale Dere[33] showed similar inclusions and colour to mortars of the 5th century. For quantification purposes, it is assumed that the proportions of materials were the same between the two phases of construction.

The tests of structural mortar samples from the 5th century yielded an average of 40 % lime, 12 % sand, and 48 % crushed brick. Applying the total volume of structural mortar (including channel masonry as well as bridge core and foundation) to these percentages, the volume of the mortars'

---

[31] Hodge, Aqueducts 98.

[32] The author is currently preparing an article on the scientific examination of mortars from the Water Supply of Constantinople and Anastasian Wall. Preliminary results can be found in Chapter 6 of Snyder, Construction Requirements.

[33] Crow/Bardill/Bayliss, Water Supply 78-79.

raw material components for the 4th-century phase has been estimated at 145 000 m³ of lime, 43 000 m³ of sand, and 174 000 m³ of brick. The volumes of raw materials in mortars from the 5th century phase were estimated to be 300 000 m³ of lime, 90 000 m³ of sand, and 360 000 m³ of crushed and powdered brick material.

Results from the analysis of channel-lining mortar indicated that, while brick aggregate and silica sand grain size was smaller, the proportion of raw materials were very similar. The required volume of lime, brick, and sand for the 4th- and 5th-century systems was the same at 4000 m³, 1000 m³, and 4000 m³ respectively.

Quantifying Raw Materials and Fuel for Material Manufacture

Three types of construction materials should be addressed in regards to their additional production requirements. These are bricks and lime used to produce mortar as well as iron clamps held in lead. Each of these materials requires a manufacturing process involving the application of high temperatures in a controlled environment. Here, we will look at the quantity of raw materials necessary to produce the end product, the number of kilns or furnace firings, as well as the amount of fuel necessary for the production process.

Raw Materials

The first material to be examined was lime. While estimates for the total lime within the mortars of these systems has already been discussed, this is misleading in regards to the total raw limestone necessary for production. The burning process results in quicklime with a density much less than the original limestone. Expansion occurs after burnt lime is rehydrated but the resulting volume of lime putty is assumed to be less. According to DeLaine, one cubic meter of limestone would yield only 0.91 m³ of lime[34]. This means that to produce the mortar needed for the 4th and 5th-century phases of the water supply, it would require 167 000 m³ and 336 000 m³ of limestone respectively.

In the case of bricks, it is assumed that little variation in volume occurs between the raw clay and the fired brick. Processing the clay to remove stone and organic materials takes out a significant portion of the total quantity, so large amounts of sand temper would have been mixed in to reduce shrinking and warping during the drying and firing process[35]. However, the type of clay as well as the type and quantity of temper affects the magnitude of shrinking and would not have been discounted during the production process. For the purpose of this study, the total volume of brick aggregate will be the same as the original total volume of raw clay.

It should be noted that the bricks used in the mortars were most likely not produced for this purpose. It is possible that they were salvaged from ruined structures as was so common in the Late Antique West[36]. It is more likely that they were stockpiled surplus bricks or wasters that would not have been functional as structural members. Wasters would make the most sense as they make up around 17 % of the total kiln load[37]. Furthermore, wasters are typically from around the periphery of the kiln and do not achieve the necessary high temperature and even firing. Scientific examination of reactions between lime and ceramics fired at various temperatures show that those fired at a slightly lower temperature have a better chemical reaction, forming stronger and more waterproof mortars[38].

The production of iron requires a large quantity of iron ore but this is dependant on the type of ore being smelted. Without knowing the exact source of the ore, it is difficult to infer the type. Using data obtained from experimental testing of iron smelting[39], a general ratio of ore-to-iron was found to be 6:1 by weight or 19:1 by volume. For the amount of iron ore needed to produce iron clamps, this calculates to a volumetric figure of 4000 m³ for the 4th-century phase and 8000 m³ for the 5th-century phase of the water supply.

Fuel

Before proceeding to the amount of fuel necessary to produce these materials, kilns and furnaces should be briefly discussed. The 5th-century Codex Theodosianus strictly prohibited lime burning within the city, indicating that the resulting pollution from this process was problematic[40]. Brick kilns were most likely also located outside the walls of Constantinople due to the space needed and smoke produced[41]. Without any archaeological evidence for these production sites, it is impossible to determine the exact size of the kilns or furnaces. For the sake of estimating the quantity of fuel for comparative purposes, figures for kiln and furnace size used by DeLaine in her detailed investigation of the construction of the Baths of Caracalla[42] have been applied here.

A moderately large lime kiln (around 100 m³ total) could hold roughly 66 m³ of limestone and produce 60 m³ of quicklime[43]. The total volume of lime from these systems would require 2535 kiln loads for the 4th century and 5085 kiln loads for the 5th-century phase. A volume of 65 m³ is assumed as

---

[34] DeLaine, Baths 112.

[35] DeLaine, Baths 114. – Ousterhout, Master Builders 129-130.

[36] Wilson, Cyrenaica 146.

[37] Ousterhout, Master Builders 131.

[38] Baronio/Binda, Pozzolanicity. – Zendri et al., »Cocciopesto« Mortars. – Böke et al., Characteristics of brick.

[39] Cleere, Ironmaking 214.

[40] Cod. Theod. 9, 17, 4.

[41] Bardill, Brickstamps.

[42] DeLaine, Baths.

[43] DeLaine, Baths 112.

the capacity for a moderately large brick kiln[44], which was estimated to require 4100 firings for the 4th-century phase and 8200 firings for the 5th-century water supply.

Based on the density of iron (7.85 t/m³)[45], the total volume necessary for the 5th-century water supply phase required 3400 t of iron and 1700 t for the 4th century. Assuming 30 kg of iron is produced from a typical iron furnace[46], this equates to 113 900 and 57 000 furnace loads for the 4th and 5th-century phases of the Water Supply of Constantinople.

Fuel was crucial for producing the amounts of quicklime, brick, and iron required for the two systems. Despite lignite deposits found within reach of the water supply and long wall[47], it remains uncertain if they were used as a fuel source in antiquity. Furthermore, petrographic analysis of mortar samples from the Water Supply of Constantinople showed traces of carbonised fibrous organic material mixed in the mortar matrix, likely spent wood fuel inadvertently included in the lime from the firing process[48]. For the purposes of estimating quantities of fuel resources, wood and charcoal were chosen based on the availability from the heavily forested areas of northern Thrace as well as data from experimental testing or historic documentation of kilns and furnaces[49].

The quantities of required wood fuel rely on the time and temperature needed to properly fire limestone, clay, and iron ore. This hinges on the calorific values of the wood used for firing and smelting and since the forests of the Thracian Peninsula are predominantly oak and beech, these were chosen as the representative woods used as fuel. All tree species have uniform calorific values of 4.5 Kcal/gm (18840 kJ/kg) if dry and around 3.5 Kcal/gm (14650 kJ/kg) if still green. Wood has been chosen as the primary fuel for producing lime and bricks based on the additional labour involved in producing charcoal. However, it should be noted that charcoal is 2.5 times more efficient than green wood, producing a higher and longer lasting heat[50].

The total firing time (at a constant 1000 °C) for a limekiln with the capacity of 66 m³ is around seven days, and would require 165 t of wood[51]. This means that an average of 2.5 m³ of wood fuel would be required to produce 1 m³ of lime. Thus, to produce the volume of lime for the 4th and 5th-century phase of the water supply would require 418 000 t and 839 000 t of wood fuel respectively.

Brick production is not as energy intensive as lime production, needing a lower minimum temperature (800 to 950 °C) and less time[52]. This necessitated only two and a half days and 40 t of wood fuel to fire a kiln with the capacity of 65 m³ according to nineteenth-century records from Italy[53]. By applying the estimated number of kiln loads required to yield the compulsory quantity of brick material for these systems, the mass of wood fuel needed for the 4th- and 5th-century phases of the water supply can be calculated at 327 000 t and 163 000 t respectively.

It was common to use charcoal in the roasting and smelting processes to generate iron from iron ore since it could easily reach the 1200 to 1300 °C needed for smelting[54]. A major centre for charcoal production in modern Turkey comes from the forests west of Çatalca (İl. Istanbul)[55] and it is reasonable to assume these forests were important for this process in Late Antiquity as well. Cleere found that these processes required a ratio of one part ore to two parts charcoal[56] meaning that the fuel essential in crafting all of the iron clamps for the water supply was 21 000 t of charcoal for the 4th-century phase and 41 000 t for the 5th-century phase.

Using the volumetric figures of necessary charcoal, we can convert this figure into raw wood. Charcoal has an average density of 208 kg/m³ and raw oak species have an average density of 760 kg/m³ [57]. This means that the production process causes a 73 % loss in density. Thompson and Young claimed that the maximum yield of a charcoal kiln would be one part charcoal from two parts wet hardwood[58]. For the sake of a reasonable estimate of necessary wood fuel, the average charcoal yield of 37 % of the total wood mass was chosen for this study. Thus, 54 000 t of oak timber was needed to produce the necessary charcoal for the 4th-century phase of the water supply. Similarly, 108 000 t of wood were needed for the 5th-century phase.

Discussion

As mentioned earlier, this particular discussion only deals with the estimation of materials and not the human application (planning, designing, site preparation, and construction, as well as construction material procurement, manufacture, and transport). A study of manpower is an integral part of understanding the scale of construction (i.e. the time and size of a labour force required to complete a given task) and is directly related to quantity of materials calculated in this paper[59]. Nevertheless, the total quantity of materials is used in this study as a means to have a unique look at how large-

---

[44] DeLaine, Baths 117.

[45] Walker, Density of Materials.

[46] DeLaine, Baths 122.

[47] Engin, maden yatakları.

[48] Snyder, Construction Requirements 173.

[49] For charcoal see Cleere, Ironmaking; for brick kilns see DeLaine, Baths 117; for lime kilns see DeLaine, Baths 112-113.

[50] Olson, Firewood 412.

[51] DeLaine, Baths 113.

[52] Ousterhout, Master Builders 130.

[53] DeLaine, Baths 117.

[54] Thompson/Young, Fuels 222. – Mattingly/Salmon, Economies 132-133.

[55] Byfield, Forest.

[56] Cleere, Ironmaking.

[57] Walker, Density of Materials.

[58] Thompson and Young, Fuels 229.

[59] While this paper does not include manpower calculations, preliminary results can be found in Chapter 7 of Snyder, Construction Requirements. New and detailed analysis using agent-based modeling is currently being carried out by the author through Leverhulme-funded project at the University of Edinburgh, under the supervision of James Crow.

Tab. 3 Total Structural volume of the long-distance Water Supply of Constantinople by construction phase.

Phase	Total Length (km)	Total Volume (m³)
4th-century Line	271	1 039 000
5th-century Line	183	2 124 000

Tab. 4 Total Volume, units, and mass of primary construction materials used in the Water Supply of Constantinople by construction phase.

Material	Volume (m³)	Number of Units	Mass (t)
4th-century Line			
Channel Lining Mortar	18 500	--	--
Structural Mortar	362 000	--	--
Facing Stones	34 000	339 000	88 500
Rubble Stone	626 000	--	1 633 000
Iron Clamps	220	305 000	1 700
5th-century Line			
Channel Lining Mortar	13 600	--	--
Structural Mortar	749 000	--	--
Facing Stones	66 000	666 000	174 000
Rubble Stone	1 295 000	--	3 380 000
Iron Clamps	440	610 000	3 400

scale construction projects in Late Antiquity relied upon the environment.

From this analysis, it is immediately apparent that the total structural volume of each phase of construction was not tied to the overall length (**tab. 3**). For instance, the 4th-century lines were almost 90 km longer than the 5th century lines but, due to the differing channel widths and average bridge size, the 5th-century phase was over twice the volume. Using larger channels and bridges was not a choice in the construction of the 5th-century water supply lines because of increased water volume and the elevation that was to be maintained over such a varying landscape. Interestingly, the typical citizen of Constantinople would likely have been unaware of the scale of this extension. Unlike the construction of the 4th-century line, which brought a massive monumental aqueduct bridge to the city's centre, the only evidence of the 5th-century extension to the majority of Constantinople's population would have been an increase in water volume.

We have seen that the long-distance Water Supply of Constantinople required millions of cubic meters of stone, brick, sand, and iron (**tab. 4**). Their individual calculations are staggering but without some frame of reference, they have little meaning. Using a combination of other large-scale construction projects (ancient and modern) and ordinary, semi-universal items of relatable size, these massive quantities of materials will be put into perspective. The total volume of rubble and facing stones used in both phases is equivalent to an area the size of an average football pitch quarried to a depth of 350 m. This would easily accommodate the height of the Eiffel Tower or Statue of Liberty, with almost 50 m to spare. It was, of course, not the case that all of this stone came from one quarry site but the equivalent was indeed taken from the local and regional environment.

This time taking into account the limestone used in mortar production, the total volume of stone needed for the 4th- and 5th-century phases of the water supply has been estimated at just over 2.5 million m³. For comparison, this is equivalent to the total estimated structural volume of the Great Pyramid of Giza[60]. It has been estimated that a total of 5.5 million m³ of stone was quarried in Rome of a four-century period[61]. Considering the long-distance water supply was one of many infrastructural projects to take place in the centuries following the founding of Constantinople, the procurement of stone must have transformed the landscape more rapidly than the environs of Imperial Rome.

The volume of mortar used in the construction of the long-distance water supply lines was second only to that of facing and rubble stone. Unlike stone, this was a composite material, needing significant additional manpower for its production. Combining channel lining mortar and structural mortar, the 4th-century phase required 381 000 m³ and 885 000 m³ for the 5th-century phase. This is more than enough mortar to fill 500 regulation Olympic swimming pools.

Compared to the volume totals of all of the other materials, the quantity of iron used to produce clamps seems deceivingly inconsequential. Combining the totals for the 4th- and 5th-century phases, a little over 5000 t of iron were needed to fasten the facing stones of the aqueduct bridges. To put this into perspective, this quantity would furnish enough iron to build more than two-thirds of the Eiffel Tower[62].

The total volume of brick aggregate in mortar is 183 000 m³ for the 4th-century phase and 366 000 m³ for the 5th-century phase (**tab. 5**). If we imagine this volume in terms of whole bricks (as at one point, before or after firing, they would have been whole) we can compare this figure to the quantities of brick needed to produce other large-scale structures of

---

[60] Levy, Giza.

[61] Lanciani, Ruins 35-36.

[62] Chanson, Legends 1.

Structural Mortar Component	Volume (m^3)	Number of Units	Mass (t)
4th-century Line			
Lime	152 000	--	129 000
Brick	183 000	28 524 000	301 000
Sand	46 000	--	73 000
5th-century Line			
Lime	305 000	--	259 000
Brick	366 000	57 201 000	604 000
Sand	92 000	--	147 000

Tab. 5 Total Volume, units, and mass of mortar components of the Water Supply of Constantinople by construction phase.

Product	Kiln / Furnace Loads	Fuel Type	Fuel Mass (t)
4th-century Line			
Quicklime	2 500	Wood	418 000
Bricks	4 100	Wood	163 000
Iron Clamps	57 000	Wood/Charcoal	54 000/21 000
5th-century Line			
Quicklime	5 100	Wood	839 000
Bricks	8 200	Wood	327 000
Iron Clamps	114 000	Wood/Charcoal	108 000/41 000

Tab. 6 Total kiln / furnace loads, fuel type, and fuel mass requirements for the production of materials used in the Water Supply of Constantinople by construction phase.

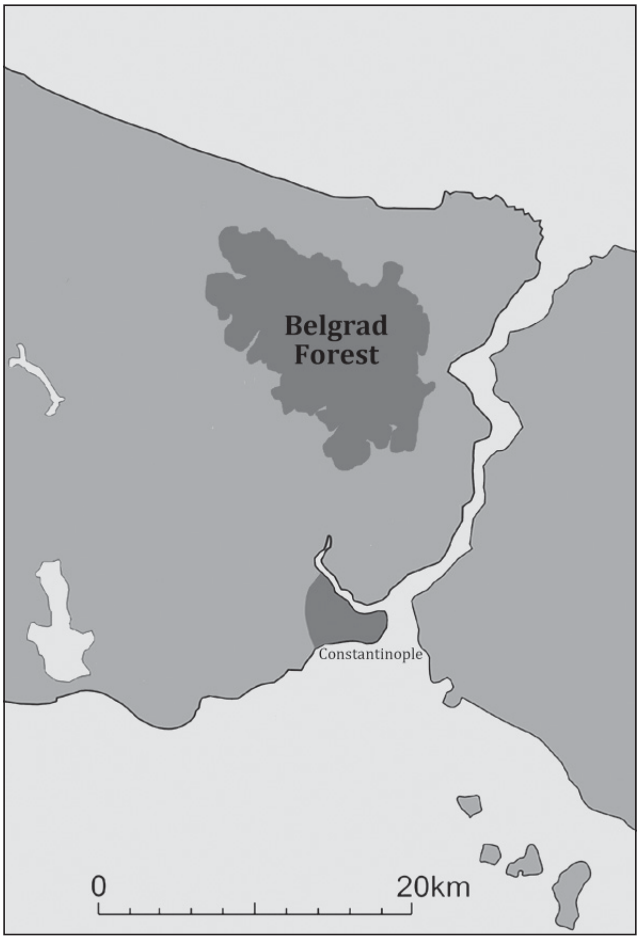

Fig. 12 Map of the eastern side of the Thracian Peninsula indicating the area of Belgrad Forest. – (Illustration R. Snyder).

antiquity. Since brick material used in the water supply was most likely produced in brickyards close to Constantinople, the average brick dimensions of this period were chosen: 0.374 m by 0.374 m by 0.046 m[63]. This equates to 28.5 million whole bricks mixed in mortars used in the 4th-century phase and 57.2 million in the 5th century. If all of these bricks were stacked side-by-side to cover the area of a football pitch, the height of the stack would be 77 m tall – well over the height and covering a greater surface area than the Colosseum in Rome.

The 4th-century phase of the water supply would have consumed 635 000 t of wood for material production while the 5th-century phase required over 1 270 000 t (**tab. 6**). Using the figure of 150 t / ha for a dense deciduous forest biomass[64], the area of land needed to yield enough wood fuel for brick, lime, and iron production for both phases is estimated to be well over 100 km^2. To obtain this much wood, an area twice the size of the Belgrad Forest would have to be cleared (**fig. 12**).

During the construction of the water supply, the worksite would have to be cleared before work began, producing large quantities of wood material. For the upkeep of the water supply system, the Codex Theodosianus states that no trees should be within fifteen Roman feet (4.40 m) of the channel or aqueduct structure, likely to ensure the root systems do not compromise the structural integrity[65]. Assuming that the majority of the system ran through forested land and this was close to the total area needed to be cleared for construction, 1.86 km^2 would deforested for the entire long-distance water supply. However, since this total is less than 2 % of the total land area needed, it is almost insignificant in the total fuel requirements.

---

[63] Bardill, Brickstamps 105.

[64] Woodall / Perry / Miles, Density of Forests 370.

[65] Cod. Theod. 15, 2, 1.

Conclusion

> »Construction, in the broadest sense of the word, includes all work performed in erecting buildings or other structures (such as bridges, subways, roads) which upon completion become integral parts of the landscape, i. e., cannot be detached from it except at a great loss in their value.«
>
> Kuznets, The Volume of Construction[66]

Estimating the construction material requirements of the long-distance Water Supply of Constantinople is not purely an exercise in presenting engaging comparisons, although this does help us understand the scale of one of the largest construction projects of the pre-industrial world. More importantly, the large numbers presented in this study are reminders of man's interaction with his environment – his ability to source, extract, transport, and apply local resources to shape the landscape to his benefit.

The procurement of building materials for the long-distance water supply system of Constantinople must have greatly impacted the landscape. There is no solid evidence of the quarry sites where these enormous quantities of sand and stone would have originated, mostly due to the dense forest cover and the rapid urban expanse of modern Istanbul. However, it is likely that instead of a few centralised quarries, stone was acquired from many sources in closer proximity to individual construction sites. The forested and mountainous environment would have been disadvantageous for long distance land transport, meaning there would be considerable logistical advantages of smaller and closer quarry sites. It is likely that the result of such material procurement is similar to that described at Sagalassos: a landscape of quarries instead of a quarry landscape[67].

More evident to the populace of Constantinople and the hinterland would have been the widespread deforestation of the surrounding environment to manufacture composite materials such as brick, lime, and iron. In addition, the production of these materials would have filled the air with caustic chemical pollutants. Due to the large-scale development of Constantinople within such a short period of time, these effects would have presented a vivid example of man's impact on the environment in Late Antiquity and beyond.

While the research presented in this paper only considers the implications of large-scale construction in Late Antiquity from the standpoint of materials, the relationship between man and his environment was integral to the workforce involved. Recent preliminary estimates using these material quantities have suggested that the long-distance water supply required a total of 10 million man-days to construct, not counting for building preparation, material production or transportation[68]. This is almost twice as much manpower required in all steps to build the Baths of Caracalla in Rome[69]. Assuming that workdays were twelve hours long, work was carried out 200 days per year, and that it took roughly 25 years to complete, building the 4th-century phase of the water supply would require an average of 2000 workers per day. Taking into consideration that the majority of the channels of the water supply were distant from large settlements, the massive workforce would have spent much of their time living in camps or temporary settlements close to the building site.

The Water Supply of Constantinople is a modern testament to the former glory of the city of Constantinople, as well to the architects, administration, and workforce involved in its construction. Like the colossal aqueduct bridges of the 5th century or the snaking channels that stretch for hundreds of kilometres, these surviving relics of bridges and channels are reminders of the importance of the infrastructural works in the hinterland of Constantinople. Not only was this system an incredible investment in time, money, and material resources, it was an investment in the resources of the hinterland. By engaging precious freshwater springs far outside the city walls, the survival of Constantinople made the city irrevocably connected to the environment from which the water came.

Acknowledgements

This paper is based in part on a Ph.D. thesis submitted and accepted by the School of History, Classics and Archaeology at the University of Edinburgh (Snyder 2013). I would like to thank Professor James Crow (Ph.D. supervisor) for his continued interest and input in this project. I would also like to thank the Institute of Advanced Studies and Dr. M. C. Carile at the University of Bologna for their support in publishing this study. I am grateful to Henriette Baron at the RGZM for inviting me to participate in the Mainz conference and to share my work in this publication.

---

[66] Kuznets, Commodity Flow 329.

[67] Degryse et al., Quarries 9.

[68] Snyder, Construction Requirements 255.

[69] DeLaine, Baths 193.

References

Bardill, Brickstamps: J. Bardill, Brickstamps of Constantinople. Oxford Monographs on Classical Archaeology (Oxford 2004).

Baronio/Binda, Pozzolanicity: G. Baronio / L. Binda, Study of the Pozzolanicity of Some Bricks and Clays. Construction and Building Materials 11/1, 1997, 41-46.

Böke et al., Charakteristics of Brick: H. Böke / S. Akkurt / B. İpekoğlu / E. Uğurlu, Characteristics of Brick Used as Aggregate in Historic Brick-lime Mortars and Plasters. Cement and Concrete Research 36, 2006, 1115-1122.

Bono/Crow/Bayliss, Water Supply: P. Bono / J. Crow / R. Bayliss, The Water Supply of Constantinople: Archaeology and Hydrogeology of an Early Medieval City. Environmental Geology 40, 2001, 1325-1333.

Byfield, Forest: A. Byfield, Within the Forest of the Long Wall. Cornucopia 7, 1994/1995, 48-51.

Çeçen, Water Supply Line: K. Çeçen, The Longest Roman Water Supply Line (Istanbul 1996).

Chanson, Legends: H. Chanson, Hydraulic Engineering Legends Listed on the Eiffel Tower. In: J. R. Rogers (ed.), Great Rivers History: Proceedings and Invited Papers for the EWRI Congress and History Symposium, Kansas City, May 2009 (New York 2009) 1-7.

Cleere, Ironmaking: H. Cleere, Ironmaking in a Roman Furnace. Britannia 2, 1971, 203-217.

Crow, History of Water: J. Crow, A History of Water at Byzantine and Ottoman Constantinople. In: T. Tvedt / T. Oestigaard (eds), A History of Water. Series 3, 1: Water and Urbanization (London 2014) 221-241.

Infrastructure: J. Crow, The Infrastructure of a Great City: Earth, Walls, and Water in Late Antique Constantinople. In: L. Lavan / E. Zanini / A. Sarantis (eds), Technology in Transition A.D. 300-650. Late Antique Archaeology 4 (Leiden, Boston 2007) 251-286.

Ruling the Waters: J. Crow, Ruling the Waters: Managing the Water Supply of Constantinople, AD 330-1204. Water History 4, 2012, 35-55.

Crow/Bardill/Bayliss, Water Supply: J. Crow / J. Bardill / R. Bayliss, The Water Supply of Byzantine Constantinople. JRS Monograph 11 (London 2008).

Crow/Maktav, Survey: J. Crow / D. Maktav, Survey in Thrace August-September 2008. Bulletin of British Byzantine Studies 35, 2009, 50-55.

Crow/Ricci, Interim Report: J. Crow / A. Ricci, Investigating the Hinterland of Constantinople: Interim Report on the Anastasian Long Wall. JRA 10, 1997, 235-263.

Dalman/Wittek, Valens-Aquädukt: K. O. Dalman / P. Wittek, Der Valens-Aquädukt in Konstantinopel. Istanbuler Forschungen 3 (Bamberg 1933).

Degryse et al., Quarries: P. Degryse / E. Bloxam / T. Heldal / P. Storemyr / M. Waelkens, Quarries in the Landscape: A Survey of the Area of Sagalassos (SW Turkey). In: P. Degryse / T. Heldal / E. Bloxam (eds), Proceedings to the QuarryScapes Workshops. Work Package 9, Deliverable No. 12. Collection of Abstracts from the Workshops: Antalya, Turkey, October 2006 – Petra, Jordan, October 2007 – Aswan, Egypt, October 2008 (Trondheim 2008) 7-10.

DeLaine, Baths: J. DeLaine, The Baths of Caracalla: A Study in the Design, Construction, and Economics of Large-scale Building Projects in Imperial Rome. JRA Supplement Series 25 (Portsmouth, RI 1997).

Döring, Gadara: M. Döring, Wasser für Gadara – Römische Fernwasserleitung im Norden Jordaniens. WasserWirtschaft 7/8, 2007, 21-25.

Engin, maden yatakları: T. Engin, Türkiye maden yatakları ve MTA' nin maden aramacılığındaki yeri. Maden Tetkik ve Arama Genel Müdürlüğü yayınlarından 194 (Ankara 1986).

Hodge, Aqueducts: A. T. Hodge, Roman Aqueducts and Water Supply (London 1992).

Krautheimer, Byzantine Architecture: R. Krautheimer, Early Christian and Byzantine Architecture. Pelican History of Art (London 1986).

Kuznets, Commodity Flow: S. Kuznets, Commodity Flow and Capital Formation, 1 (New York 1938).

Lanciani, Ruins: R. A. Lanciani, The Ruins and Excavations of Ancient Rome. A Companion Book for Students and Travelers (Boston 1897).

Levy, Giza: J. Levy, The Great Pyramid of Giza: Measuring Length, Area, Volume, and Angles (New York 2005).

Maktav et al., Remote Sensing: D. Maktav / J. Crow / C. Kolay / B. Yegen / B. Onoz / F. Sunar / G. Coskun / H. Karadogan / M. Cakan / I. Akar / C. Uysal / D. Gucluer / B. Geze / G. Ince, Integration of Remote Sensing and GIS for Archaeological Investigations. International Journal of Remote Sensing 30/7, 2009, 1663-1673.

Mango, Water Supply: C. A. Mango, The Water Supply of Constantinople, In: C. A. Mango / G. Dagron (eds), Constantinople and its Hinterland. Papers from the Twenty-seventh Spring Symposium of Byzantine Studies, Oxford, April 1993. Publications of the Society for the Promotion of Byzantine Studies 3 (Aldershot 1995) 9-18.

Mattingly/Salmon, Economies: D. J. Mattingly / J. Salmon (eds), Economies Beyond Agriculture in the Classical World. Leicester-Nottingham Studies in Ancient Society 9 (New York 2001).

Meiggs, Trees: R Meiggs, Trees and Timber in the Ancient Mediterranean World (Oxford 1982).

Olson, Firewood: S. D. Olson, Firewood and Charcoal in Classical Athens. Hesperia 60/3, 1991, 411-420.

Ousterhout, Master Builders: R. Ousterhout, Master Builders of Byzantium (Philadelphia 2008).

Ruggeri et al., GIS-based assessment: F. Ruggeri / M. Crapper / J. Crow / J. R. Snyder, A GIS-based assessment of the Byzantine water supply system of Constantinople. Water Science & Technology: Water Supply 17/4, 2017 (forthcoming).

Snyder, Construction Requirements: J. R. Snyder, Construction requirements of the Water Supply of Constantinople and Anastasian Wall [unpubl. Diss. Univ. Edinburgh 2013].

Thompson/Young, Fuels: G. Thompson / R. Young, Fuels for the Furnace: Recent and Prehistoric Ironworking in Uganda and Beyond. In: M. Van der Veen (ed.), The Exploitation of Plant Resources in Ancient Africa. Proceedings of the 2nd International Workshop on Archaeobotany in Northern Africa, held June 23-25, 1997 in Leicester, UK (New York 1999) 221-239.

Walker, Density of Materials: R. Walker, Density of Materials. www.simetric.co.uk/si_materials.htm (11/07/2017).

Ward-Perkins, Building Methods: J. B. Ward-Perkins, Notes on the Structure and Building Methods of Early Byzantine Architecture. In: D. Talbot Rice (ed.), The Great Palace of the Byzantine Emperors, Second Report (Edinburgh 1958) 52-104.

Wilson, Cyrenaica: A. Wilson, Cyrenaica and the Late Antique Economy. Ancient West and East 3/1, 2004, 143-154.

Woodall / Perry / Miles, Density of Forests: C. W. Woodall / C. H. Perry / P. D. Miles, The Relative Density of Forests in the United States. Forest Ecology and Management 226, 2006, 368-372.

Zendri et al., »Cocciopesto« Mortars: E. Zendri / V. Lucchini / G. Biscontin / Z. M. Morabito, Interaction Between Clay and Lime in »Cocciopesto« Mortars: a Study by ^{29}Si MAS Spectroscopy. Applied Clay Science 25/1, 2004, 1-7.

Zusammenfassung / Summary

Ausschöpfung der Landschaft: Eine Quantifizierung der Materialressourcen, die für den Bau des Fernwasserversorgungssystems von Konstantinopel genutzt wurden

Im 4. und 5. Jahrhundert erlebte das neue Konstantinopel eine rapide Entwicklung von einer kleinen Stadt zu einer großen Metropole. Die plötzliche Einwanderungswelle in die Stadt führte in kürzester Zeit dazu, dass viele Infrastrukturinvestitionen nötig wurden, vor allem in ein leistungsfähiges Frischwasserversorgungssystem. Der Bau von Kanälen und großen Brücken für die Fernwasserversorgung Konstantinopels begann in der Mitte des 4. Jahrhunderts. Das System erstreckte sich westlich der Stadt weit in das Hinterland und wurde von Quellen versorgt, die Hunderte von Kilometern entfernt lagen. Bevor dieses Wasser die boomende Stadt erreichte, war die Abhängigkeit der Bevölkerung von der Umwelt des Hinterlandes noch größer als bei der Erbauung des massiven Wasserversorgungssystems.

In diesem Beitrag werden die Materialien quantifiziert, die für die Erbauung des spätantiken Wasserversorgungssystems benötigt wurden. Von ihrer Größe bis hin zur Produktion der Teile war diese Struktur ein logistisches aber auch technisches Meisterwerk des damaligen Ingenieurwesens. Diese Studie hat zum Ziel über eine quantitative Aufrechnung des Rohmaterials, das in Konstantinopels Hinterland abgebaut und für den Bau der Wasserleitung verwendet wurde, zu erforschen, in welchem Maße die Planer und Erbauer auf die naturräumlichen Ressourcen zurückgriffen.

Exploiting the Landscape: Quantifying the Material Resources Used in the Construction of the Long-distance Water Supply of Constantinople

In the 4th and 5th centuries, the new city of Constantinople underwent a rapid transformation from a small town into a great metropolis. The flood of migration to the city created an immediate need for many infrastructural works, most importantly a supply system to furnish large quantities of fresh water. The construction of channels and great bridges of the long-distance Water Supply of Constantinople, starting in the mid-4th century, stretched far to the West of the city, relying on springs hundreds of kilometres away. Before this water was to reach the population of the booming city, man's reliance on the hinterland environment of Constantinople is nowhere more evident than in the construction of this massive water supply system.

This paper presents a quantitative examination of the materials used to construct the Late Antique Water Supply of Constantinople. From its overall structural volume to the quantity of fuel necessary to produce its components, this system was as much a marvel of logistical prowess as engineering might. However, it is the ultimate aim of this study to uncover the planners', builders', and administrators' reliance on the environment through a comprehensive summation of the raw materials removed from and reapplied to Constantinople's hinterland landscape.