# AN ENGINEERING EXPLORATION OF THE WATER SUPPLY SYSTEM OF CONSTANTINOPLE

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Thesis submitted for the degree of
Doctor of Philosophy

UNIVERSITY OF EDINBURGH

SCHOOL OF ENGINEERING

2018

# Declaration

I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where stated otherwise by reference or acknowledgment, the work presented is entirely my own.

Kate Ward April 2018

The sections outlined below include work previously included in the publications detailed. In these joint author publications, I was the first author and they were my own work, under the guidance of my supervisors. Preprint versions of the publications written during this PhD project are included in Appendix D.

| Title | Publication | Section |
|---|---|---|
| Water-supply infrastructure of Byzantine Constantinople | Journal of Roman Archaeology (2017) | 6.2.2,<br>6.3-6.4 |
| The Byzantine cisterns of Constantinople | Water Science and Technology: Water Supply | 6.2.1,<br>6.2.2 |

# Acknowledgements

In May 2013 I was in Istanbul and visited the Basilica cistern and the Bozdoğan Kemeri. As a curious civil engineer I wondered how the whole system had worked and assumed that someone, somewhere knew the answer. It turned out that not only was I wrong, but also that I was the fortunate person who, one year later, was given the chance and the support to work out how it all connected.

This PhD is built on a great deal of academic and moral support. Thank you to my three-person supervision team. Prof. Jim Crow has welcomed and introduced us engineers to all things Constantinople, successfully guided us around Istanbul and been enthusiastically impressed by anything remotely technical we showed him. Prof. Martin Crapper, who, with Jim, had the original idea and obtained the funding from Leverhulme for the project and, most importantly, had the good sense and vision to obtain the funding for an additional PhD student from the EPSRC. This enabled two of us to work on the project, which was incredibly important in terms of what we were able to focus on and find out. And finally I am grateful to Dr. Simon Smith who has moved in to the role of first supervisor and been of great help to me during the final stages with his thoughtful and engaged feedback.

Throughout the project Dr. Kerim Altuğ has been generous with both his time and data. I would like to thank him for giving us his time when we were in Istanbul, for providing his ArcGIS map at the start of the project and for the numerous times he has sent me photos and plans of interesting cisterns and channels in Istanbul. He has become a true colleague and friend – teşekkür ederim!

Working on a subject that is a bit odd and does not fit with what other researchers in the department work on could have been an isolating experience but that has not been the case. My thanks to Filipe and the iDynamics group for taking the academic orphans under your wing. To my fellow John-Muirians, past and present, thank you for all the support and coffees, cakes, pub-quizzes, barbeques and paella.

For enormous forbearance when the PhD has become all-consuming, and at other times for all the fun, support, encouraging words, cistern-based puns and songs, thank you to my friends Shona, Heather, Graeme and Nome.

Thank you to Nuala and Jim, for putting me up for the first few months of the PhD and for letting me use Canal House for numerous writing retreats. Thank you to Pippa and Graeme, for letting me stay at their house for eight months in the company of their cat Louie while they were away in Germany.

Thank you to my sister Lucy, who has dispensed almost daily messages of support, along with fixing me with her physio advice when I have been sitting at my desk for too long and who has, with my brother-in-law Duncan, made me proud aunt to baby Izzy. Thank you to my brother Fergus for being unreservedly proud of his big sister. And for Patrick, who would no doubt have made fun of me for ending up making a rather rudimentary water management "computer game".

The biggest thanks go to my parents John and Pauline, who have been there from start to finish, believing in me, persuading me to believe in myself and, by reading everything that I have written, learning far more about the water supply of Constantinople than they really needed to. Without you I could not have done this.

And finally a heart-felt thank you to the fellow members of the Constantinople Water department: Riley and Francesca. It has been so important to me that I have been able to share this journey with both of you.

# Abstract

Before this research study began, relatively little was understood of the water supply in Constantinople, particularly within the walls of the city. Archaeological work had focused on collecting details of 160 cisterns and a small number of channels and pipes were incidental finds in other excavations. Although no-one had considered the water supply in Constantinople as a whole, the evidence seemed to indicate a sophisticated water management system. With the available data fragmented, and the potential for more evidence limited to serendipitous finds associated with construction work, the only way to move the understanding of the water supply forward is to take a radically different perspective: civil engineers are well placed to envisage the water supply as a working system and make use of their modern design skills and tools to fill in the gaps between the fragmented data.

This reimagining of the water supply system was driven by a key piece of knowledge: the water supply worked, and worked for many centuries. That fact, combined with the fragments of physical and literary evidence, the largely unchanged landscape and the fundamental physical laws governing gravity-fed water systems, are enough to start filling in the information to create a complete system.

The core work in reimagining the water supply system has been developing an understanding of the physical infrastructure of the distribution system. Although the two most recent and comprehensive studies appeared to agree that there were about 159 cisterns in the city, close examination of the available data showed that there were actually 209 with the possibility of more. An evaluation of the aqueduct routes in previous studies highlighted inconsistencies with newly available evidence: alternative routes were designed that tied together the available evidence, providing a consistently downhill route, shorter and more straightforward to construct. Having established the number and spread of cisterns and the locations of the aqueducts, it was possible to create a network delivering water from the aqueduct channels to the cisterns for collection by the public.

Consideration has also been given to what occurs at either end of this physical infrastructure. At the upstream end, quantifying and characterising the water source defines the water available to distribute and helps to indicate the purpose of the cisterns. At the downstream end, developing even a basic model of water consumption has enabled the distribution network to move from a static artefact to a system with a quantifiable purpose.

The combination of the physical infrastructure, inflow data and demand assumptions in an agent-based model demonstrate that the decisions and assumption made within each element work together and allow a fourth element, management, to be considered.

The agent-based model of the water supply enables consideration of a dynamic system and the exploration of a number of “what if?” scenarios. This exploration concludes that the cistern-based distribution system probably developed because of fluctuations in inflow. It may have been possible for the city to use a merged arrangement on the Aqueduct of Valens inflow, but the burden of pro-active management required to make it successful suggests that a parallel arrangement is more likely. There was likely to be an interconnection between the two main aqueducts, which would have enabled the use of water stored in the largest open-air cisterns.

# Lay summary

Constantinople – one of the most important cities in history – would not have been successful without the skill and innovation of its water engineers, who brought water from distances unparalleled for the time and used a complex network of cisterns to distribute water throughout the city. Today, little evidence of this system survives and it is under threat from construction work in modern Istanbul.

Most previous work on the water supply in Constantinople has focused on the 400-km-long Aqueduct of Valens that brought water into the city from the Thracian hinterland; the scores of cisterns – man-made structures for the storage of water, which in Constantinople ranged from 2 to 300,000 $m^3$ – have not previously been studied comprehensively or from the perspective of an operational system. The aim of this thesis is to investigate whether, and how, an engineering approach can transform our understanding of the archaeological evidence of the water supply system of Constantinople.

The project is centred around the design of a network capable of using the storage of the cisterns to distribute sufficient water to the population of the city. The remains of the original system have been incorporated into a re-imagined system using engineering judgement and secondary sources of information such as the landscape of the city, textual descriptions and contextual knowledge of the technology of the time. This network design has been combined with models of inflow and water demand into an operational model of the water supply system that has been used to investigate how the system could have been managed.

An updated total for the number of cisterns and new route proposals for the aqueducts within the city are results from the project and the water supply system model is a key outcome that has enabled an understanding of the management required to ensure that enough water reached all parts of the city. The results of the thesis are of specific interest to archaeologists and historians working on Byzantine Constantinople, and more generally to engineers and technologists working in heritage and archaeology projects.

## Acronyms

| | |
|---|---|
| ABM | Agent-based model(ling) |
| CFD | Computational Fluid Dynamics |
| CIL | Corpus Inscriptionum Latinarum (a comprehensive collection of ancient Latin inscriptions maintained by the Berlin-Brandenburg Academy of Sciences and Humanities: cil.bbaw.de) |
| Cod. Just | Justinian law codes. Translated by Frier *et al.* (2016) |
| Cod. Theo | Theodosian law codes. Translated by Pharr (1969) |
| Front. | Frontinus, *De aquis Urbis Romae*, available online: http://penelope.uchicago.edu/Thayer/e/roman/texts/frontinus/de_aquis/text*.html |
| masl | Metres above sea level |
| MCM | Macrophysical Climate Modelling |
| Plin. Nat. | Pliny the Elder, The Natural History, trans. Bostock & Riley, available online: http://www.perseus.tufts.edu/hopper/ |
| Vit. | Vitruvius, On Architecture, Book VIII Water trans. Gwilt, available online: http://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius/8*.html |

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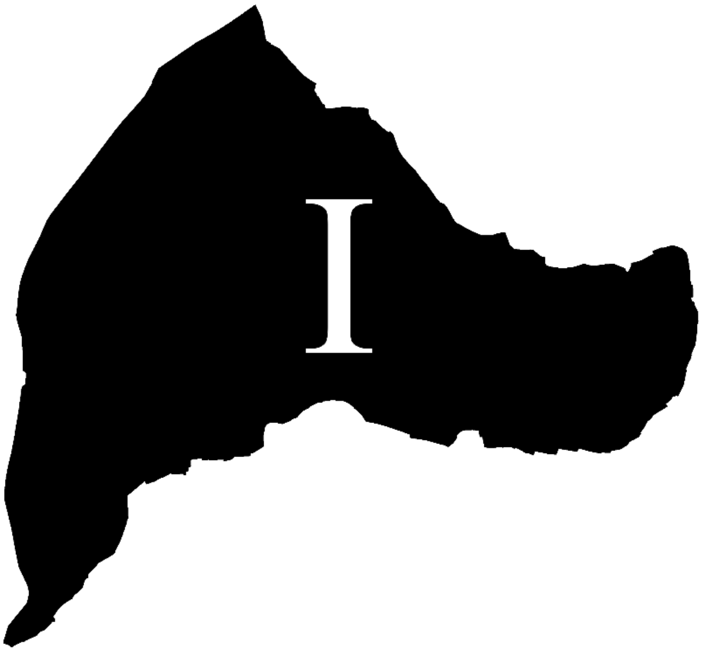

## 1.1 Introduction

In the mid 1540s Frenchman Pierre Gilles, intrigued that some Ottoman residents of Constantinople were able to draw water and catch fish from holes in their courtyards, 'rediscovered' the Basilica cistern.[1] Rowing through an underground forest of submerged pillars with a flaming torch, he was able to explore the water storage structure constructed by the Emperor Justinian 1000 years previously. Today, five hundred years later, the cistern is no longer used to store water but has been visited by millions of tourists, intrigued by this curious piece of Byzantine-era engineering beneath the streets of modern Istanbul. The Basilica cistern is impressive – a man-made cavern 65 m wide, 138 m long, with 420 columns supporting the roof – but unknown to all those visitors, it is only one part of the story of the water supply of Constantinople.

Although Constantinople was surrounded by water, it had no substantial sources of fresh water nearby; yet, as historical records attest, the city's water supply drew much admiration from visitors. Unfortunately, the physical evidence of the water supply system that remains today is fragmentary and ancient texts provide little description or detail: nothing offers a clear picture of how the much-admired system functioned. Much of Byzantine Constantinople has been lost, first beneath Ottoman Constantinople and then modern Istanbul. What remains is an incomplete jigsaw puzzle that hints at a complex system of water storage and management that differs significantly from its predecessor as the capital of the Roman Empire, and most obvious comparator, Rome.

Archaeologists and historians are interested in what the water supply system can tell them about both daily life in the city and the management and decision making structures that allowed the water system to function but in the mid-1990s Byzantinist Cyril Mango recognised that not enough "proper archaeological investigation [has been done on the water supply] to treat this topic as fully and accurately as it deserves" (Mango 1995). Since then significant archaeological work has been undertaken. The Aqueduct of Valens, a channel at least 426 km long[2] and constructed in two phases in the mid-4th and early-5th

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[1] See Byrd (2008) pp 100-102 for Gilles account of the discovery (in reality, "rediscovery" is the wrong word as the cistern was almost certainly used by the Ottoman water supply at this point).

[2] In fact, recent research suggests that the channels may have been 565 km long (Ruggeri *et al.* 2017).

century that was the main provider of water for Constantinople has been mapped. Within the city, archaeological work has focused on recording the cisterns, structures of varying sizes and forms but all designed to store water. Nine were mentioned in Gilles' writings on Constantinople; by the late nineteenth century Forchheimer and Strzygowski (1893) were able to list 70 of which they visited and described 45 in detail; during the 20th century numerous scholars noted multiple cisterns and Müller-Wiener (1977) recorded 75. The two most recent and comprehensive studies have expanded the number of known cisterns considerably: in Crow, Bardill and Bayliss (2008) a bibliographical concordance identified 161 and Altuğ (2013) created a database of 158 cisterns.

### 1.1.1 Study motivation

The number of cisterns identified clearly show how integral they were to the water supply system of Constantinople yet, to date, little work has been done to try and understand how the system operated. Archaeological work has led to an accumulation of elements of the system but has not substantially increased the understanding of how the water supply operated. Nor, in the context of Constantinople, can further archaeological work be expected to provide that increased understanding. Unlike the ancient cities of Pompeii and Ephesus where the water infrastructure is accessible and preserved to a larger extent, evidence of Constantinople's water supply will only ever be fragmentary.

Archaeologists can identify more elements and improve on the details known about the cisterns, channels and pipes discovered, narrowing the dates for construction and use, but they cannot advance the understanding of how the system operated. To do so requires a different perspective and a new set of tools.

Civil engineering, concerned as it is with providing the infrastructure which underpins all of modern civilisation, is well versed in the approaches and technologies used to supply water to citizens. Such familiarity is clearly an advantage in developing an understanding of how a particular water supply system worked. More than that, engineering design combines both the microscopic and the macroscopic: a thorough understanding of the details is integrated with the big picture to produce a functional whole.

In Constantinople we have a collection of such details – cisterns and fragments of channel – although they have not yet been examined by engineers, and, although its full form is not known, there was a water supply system and it functioned well. The water supply infrastructure served the city for over 1000 years and was resilient and adaptable enough to survive the changing populations, multiple natural disasters and sabotage.

### 1.1.2 Aim, objectives and scope of the study

The aim of this research is to investigate whether and how an engineering approach can transform our understanding of the archaeological evidence of the water supply of Constantinople. In order to achieve this aim I[3] will:

1. Collate and reappraise the available evidence of the water system from an engineering perspective,
2. Develop a water demand framework which approximates water use in the sixth century,
3. Design a functioning water network that logically connects the known elements, and
4. Model the water network to assess water management requirements that would satisfy the water demand.

A city-wide water supply is enormously complex, particularly one that operated in various forms for over 1000 years. The investigation is also necessarily broad, drawing on data from a wide range of sources and disciplines. In order to be manageable, the limits of the investigation must be set. In geographical terms, I focus on the water-supply system within the Theodosian Walls – so the city Regions XIII (Sycae, now Galata) and XIV are omitted,[4] and the aqueducts

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[3] Regarding the use of the first person in this thesis: this is not science, where a non-biased objective viewpoint might be claimed. Nor is the work so firmly grounded in established standards or previous research that it can fall back on authority or authoritative work to support reasoning. This project largely relies on engineering judgement to find a way forward – it does not rely on some established 'Engineer' that can be referenced, but to me, the engineer making the judgement.

[4] In the *Notitia Urbis*, which documents the assets and infrastructure present in the city at about 425 A.D., the city was split into 14 regions. Twelve of these regions were on the historical peninsula contained by the city walls with Region 13 located across the Golden Horn and the 14th region in an unknown location. See Matthews (2012) for descriptions of the regions and Map 2.6 for locations.

outwith the city walls are not considered in depth (the Aqueduct of Valens is being explored in a parallel study). Temporally, the study focuses on the 6th century – the point at which the majority of the water infrastructure was thought to be in place and the population is agreed to have been at a peak before being ravaged by plague. New archaeological work is also outwith the scope of the study, which will focus on what can be gained from the existing evidence by using a different approach and perspective.

Clearly, this study differs from a typical engineering project – the work will not lead to a constructed object or system, whose existence is proof of the validity of the design. Nor is this project a piece of scientific research, with a hypothesis and experimental method designed to produce results. It is an investigation, an exploration of what it is possible to understand and deduce about the water supply system.

The "correct" answer of how the water supply worked is unobtainable. Piecing together the precise nature of the system would require a comprehensive knowledge of four main contexts: topographical, political, personnel and technological. It would be near impossible to reconstruct the workings and development of a modern system only from its physical infrastructure. So is it worth it to try with a 1500-year-old system? What can we hope to gain? Much can be learnt from reimagining the water supply: the questions that arise and must be answered in the process of creating a functional network provide insight into both the water supply and the city of Constantinople as a whole.

### 1.1.3 Impact and significance of the study

The intended outcomes of this project have the potential to be significant across multiple levels and for a number of distinct communities. In terms of knowledge creation, this project contributes to our understanding of the number and location of elements of the water supply and generates new understanding of how the system as a whole functioned and was operated. In practical terms, the project contributes a solution to the particular case of Constantinople, where fragmentary evidence had stalled the progress of work on the water supply; a system-level perspective is able to integrate the available data and bridge knowledge gaps. Such an approach may be useful in other archaeological contexts. This project is a good example of novel and fruitful trans-disciplinary work, showcasing the benefits not only of bringing an engineering perspective to an archaeological problem but also of what engineering research can gain from performing research that draws on the broader experience of a design or industrial setting.

The Leverhulme funded research programme “Engineering the Byzantine water supply: procurement, construction and operation” combines this project, another PhD project, by Francesca Ruggeri (Engineering the Byzantine water supply of Constantinople: mapping, hydrology and hydraulics of the long aqueducts outside the City) investigating the hydraulics and operation of the Aqueduct of Valens, and a project by post-doctoral researcher J. Riley Snyder, examining the construction challenges of the water supply infrastructure. Together these projects form the most comprehensive and detailed investigation of Constantinople’s water supply to date.

The water supply of a sizeable city is an enormous and complex undertaking, as is the task of studying it. There is significant interconnection between my work and Francesca Ruggeri’s – my model is dependent on her investigation of spring hydrology and creation of a number of year-long daily inflow data series. In return, the results from my model provide another perspective for some of the questions that arise from her investigation of the Aqueduct of Valens.

This specific project has the opportunity to impact three distinct communities: academics working in the field of Byzantine Constantinople and urban history, the public including residents of Istanbul and tourists, and academics working in engineering research.

Academics working on Byzantine Constantinople or urban history can benefit from the knowledge created by the project and also the demonstration of what the system-wide approach and engineering perspective can bring to archaeological problems.

There is an interest in this work from the general public and from those in Istanbul in particular. The Basilica cistern is one of Istanbul’s most popular tourist attractions. Having an awareness of the extent of the system is particularly important here as the Byzantine system is vulnerable to the modern developments of Istanbul – as the city expands further into Thrace, the remains of the Aqueduct of Valens are increasingly under threat.[5] Within the city, it is likely that there are still unknown cisterns beneath the modern streets; new developments threaten these structures but are also most likely to uncover them. If there is a wider knowledge of the system it is easier to identify, protect and preserve new finds. Having had several strangers stop and try to explain how the bit of water supply infrastructure I was examining fitted together with other areas of the city, I know that there is an interest and pride in the water supply that forms one of the many layers of history in Istanbul. Improving the accuracy of people's knowledge in the history of their city can only be a good thing.

The final community that could benefit from the outcomes of this project is the engineering research community. Traditionally engineering research tends toward narrow, focused work with a heavy reliance on a scientific approach, yet engineering itself is much broader and manages to integrate a range of philosophies and approaches to meet the required goals of a project. This project is an example of how engineering research can embrace the wider engineering approach and deliver fruitful and interesting outcomes.

## 1.2 Thesis Outline

The thesis is in three broad parts: firstly, in chapters Two and Three, the context of the study is established. In the second part of the thesis, the framework of the engineering approach is explained and the ground work in examining and understanding the base data is described. The final part of the thesis focuses on the reimagining of a functioning system, the modelling of this system and the conclusions that can be drawn from it.

**CHAPTER TWO** provides a background and context for readers not familiar with the Byzantine city of Constantinople, with a focus on elements pertinent to the

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[5] For instance, the new Istanbul airport in Arnavutköy cuts across the route of the Aqueduct of Valens.

water supply, and the evidence available, both physical and textual for studying it.

There has not been a great deal of study into the water supply in Constantinople. In **CHAPTER THREE**, previous investigations into broader aspects of ancient water supply systems are reviewed. As cisterns are such an unusual and key element of this system, their development as a technology around the Mediterranean is examined. As the source of much of what is known about Roman and Late Antique water systems, water supplies in other ancient cities are discussed. Finally, the chapter focuses on other instances where engineers have worked on archaeological water problems.

**CHAPTER FOUR** discusses how we can use engineering to progress the seemingly intractable problem of the water supply. The choice of engineering approach is important and purposefully moves away from the positivist perspective typical of science-based engineering research and towards the constructivist and interpretivist perspectives that are closely aligned to the engineer as designer and constructor.

**CHAPTER FIVE** considers two of the dynamic elements of the water supply that will be combined in the reimagined system: inflow and demand. The inflow is dependent on the aqueducts outside the city. The 4th and 5th century phases of the Aqueduct of Valens have been considered in depth in the parallel project by Ruggeri. I incorporate Ruggeri's work creating daily inflow data into my model of the system within the city and present some basic investigations on flows in the Aqueduct of Hadrian. The final part of this section is on demand, or water use, and looks at how a city-wide model of water demand can be built up from the information available on population and other water users.

**CHAPTER SIX** considers the static element of the water supply system: the physical infrastructure that makes up the network. Parts of this section include work that I have published in the Journal of Roman Archaeology and Water Science and Technology: Water Supply, re-examining the aqueduct routes within the city, the number of known cisterns and examining how the cisterns and aqueducts could be interconnected.

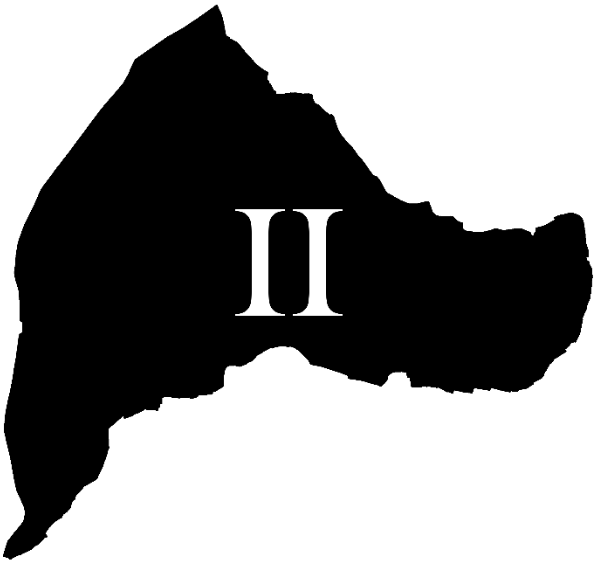
**CHAPTER SEVEN** describes the agent-based model created to represent the water supply system of Constantinople. The model incorporates a mass-balance model of the distribution system and an independent water-collecting population. When combined together in the agent-based model with daily inflow data, the management required to achieve satisfactory performance can be investigated. Some of this work was presented at the one-day workshop *Byzantine water and engineering in Constantinople and Thessaloniki: new results and approaches.*

In **CHAPTER EIGHT** the model results and deeper understanding of the system are brought together in a discussion of four key questions about the wider system. These questions cover aqueduct arrangements, spring flow characteristics, the role of management within the system, and interconnections of the system.

**CHAPTER NINE** concludes the thesis, summarising the new understanding of the water supply system developed over the course of this project, reflects on the process of applying engineering in an archaeological context and suggests some future lines of research on the water supply system of Constantinople.

# Constantinople: cistern city

Background and context for the development of Constantinople and its water supply – physical evidence – textual sources



"The city is truly a city and no longer a mere sketch"[6]

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[6] Themistius (*Oratio* XI.151a cited in Crow *et al.* 2008, p.224), pronouncement after the Aqueduct of Valens arrived in the city.

## 2.1 Introduction

1400 km east of Rome, Byzantium was a Greek fishing settlement located at the tip of a promontory at the end of the Thracian peninsula. In the early 4th century it was selected by the Emperor Constantine as the site of his new city, Constantinople. It was inaugurated in 330[7] and shortly after became the capital of the Roman Empire. The city continued as the seat of power of the Empire (the Eastern Roman Empire but today known as the Byzantine Empire) until it finally succumbed to the Ottoman conquest of 1453. From that point, Constantinople served as the capital of the Ottoman Empire until the creation of the modern state of Turkey when in 1930 it officially became Istanbul.

Although Constantinople's long survival as one of history's most important cities can be attributed to the strategic and commercial advantages of its position, it could not have survived without a water supply that overcame the natural disadvantages of its location. With few local water resources (Mango 1995, 9-10), the city had to depend on water brought in from the Thracian peninsula over considerable distances. The water supply to Constantinople was developed over a millennium, from the earliest infrastructure supplying Byzantium (before the foundation of Constantinople) to the cisterns constructed in the final period before the Ottoman conquest of the city in 1453. The first stage in understanding the water supply from the engineering perspective is to assimilate the available data and build a picture of what is known about the water supply system and the city that it served. Although what remains of the water supply system is fragmentary, an overview can be created by combining the physical evidence with various textual sources and considering the principal factors of topographical context, resource availability and population change.

In the pre-Constantinopolitan settlement of Byzantium, population was concentrated in the low-lying valley at the east end of the peninsula and an aqueduct brought water in from the Belgrad Forest to augment the meagre local water resources (Mango 1985, p. 18-21). When Byzantium became Constantinople in the 4th century, the population grew and the occupied area increased beyond the bounds of the valley, moving into the higher ground to the

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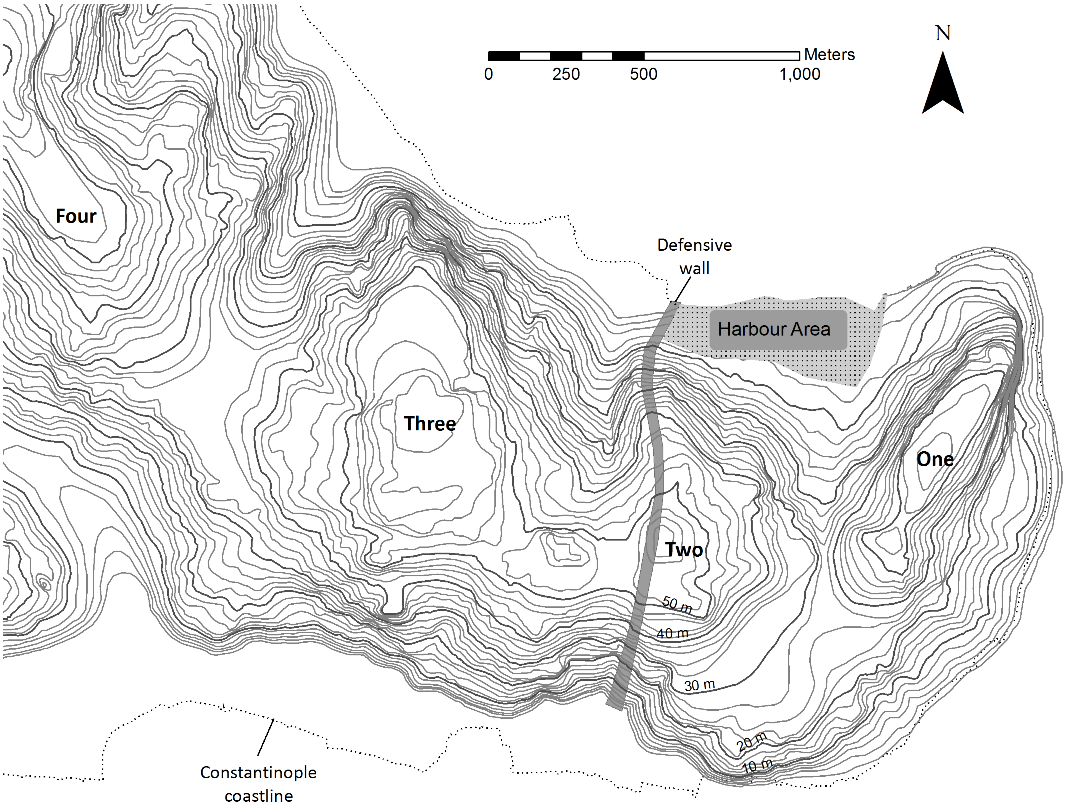
[7] All years given are AD.

west. Not only was there an increased demand for water because of the population growth, but there was also a need for water to be supplied at a higher elevation in order to reach the new areas of the city. To achieve the increased elevation, a new aqueduct was constructed that exploited springs in the Thracian hinterland at a distance from the city so great that the aqueduct was the longest in the Roman world (Çeçen 1996a, Crow *et al.* 2008). For a time, this aqueduct appears to have satisfied the water demand from the population but in the 5th century a second, parallel, aqueduct was added which exploited springs even more distant (Crow *et al.* 2008), creating an aqueduct system over 560 km long (Ruggeri *et al.* 2017). Although the population continued to grow until the devastating plagues of the 6th century, the municipal authorities did not appear to seek more water sources or construct more aqueducts. Perhaps the second aqueduct brought a large enough increase in water entering the city to satisfy future population growth; however, while it was being constructed, the authorities also started to construct cisterns, suggesting that water demands continued to grow and a different strategy was employed to store and manage the water available. Given that the authorities had already had to construct the two longest aqueducts in the Roman world to obtain its water, they may have been reluctant or unable to continue the typical Roman strategy of constructing more and more aqueducts to meet water needs. The cisterns, ranging from tiny room-sized structures to enormous open-air reservoirs continued to be constructed all over the city and throughout the time period of Byzantine Constantinople (Altuğ 2013, Crow *et al.* 2008, p. 125-155). As the city adjusted to circumstances and its population changed, cisterns were constructed to adapt the water supply to the needs of the time. In the later stages of Constantinople, parts of the water supply, particularly the long aqueducts, were damaged beyond repair (*Deeds of John and Manuel Comnenus* 6.8 trans. Brand 1976) and adaptations to use closer, less plentiful sources may have been made.

This vignette is fleshed-out below, initially with a more detailed consideration of the key stages of infrastructure development: the pre-Constantinople water infrastructure; the development of the Aqueduct of Valens in two phases; and the spread of the cistern across the city. This is followed by an examination of the previous work on the physical evidence of the system, both cisterns and channels, which will provide some of the base data for creating the reimagined network model. Then there follows an examination of the textual sources – law codes, an inventory, orations and travellers' accounts, which provide further detail and nuance on the management, purpose, development and layout of the system.

## 2.2 Development of the water system

### 2.2.1 Water resources and infrastructure pre-Constantinople



Map 2.1: Topographical context of Byzantium. It occupied Hill One and Hill Two of the peninsula. Based on Mango (1985 & 2001).

As shown in Map 2.1, Byzantium was limited to the eastern end of the peninsula that would become Constantinople (Mango 1985, 14-16). Only in the earliest stages of Byzantium could the people rely on what was available in the vicinity of the settlement: wells fed by groundwater, rainwater collected in small cisterns and, perhaps, water collected from the Lycus, a watercourse that was outside the settlement's defensive wall. Some wells that still hold water today have been recorded in Hill One (Özkan Aygün 2010, 67-72) which suggests (although there is no evidence linked to this time period) that this means of water supply was available to the early inhabitants of Byzantium.

By the second century Byzantium had constructed an aqueduct under the auspices of the Emperor Hadrian.[8] Little is known of this aqueduct but traces of Roman structures within bridges in the Ottoman Kırkçeşme water supply system are thought to be part of the Aqueduct of Hadrian (Tursun Bey & Gilles, cited in Crow *et al.* 2008, p. 242-43) and it is assumed that the two systems shared the same water source in the Belgrad Forest north of the city. No physical remains have been discovered of the Aqueduct of Hadrian but, as it continued to play a key role throughout the Byzantine era of Constantinople (Crow *et al.* 2008 13, p. 20), the elevation of the aqueduct can be estimated based on later textual evidence. The Aqueduct of Hadrian served the Basilica cistern, Imperial Palace and the public baths (*Cod. Just.* 11.42.6, Frier *et al.* 2016); a route based on this information was drawn by Bayliss in Crow *et al.* (2008) and is illustrated in Map 2.2, with the aqueduct located at about 30 masl (metres above sea level) mid-way up the north slope of the ridge. This positioning is consistent with supplying water to Byzantium – Mango (1985, 1995) places the main part of Byzantium in the north-facing valley around the harbour and the religious centre on the acropolis on Hill One. The route shown in Map 2.2 represents the understanding of the water supply prior to this research. In Chapter Six, there is a re-examination of the available data and a new interpretation of the route of the Aqueduct of Hadrian.

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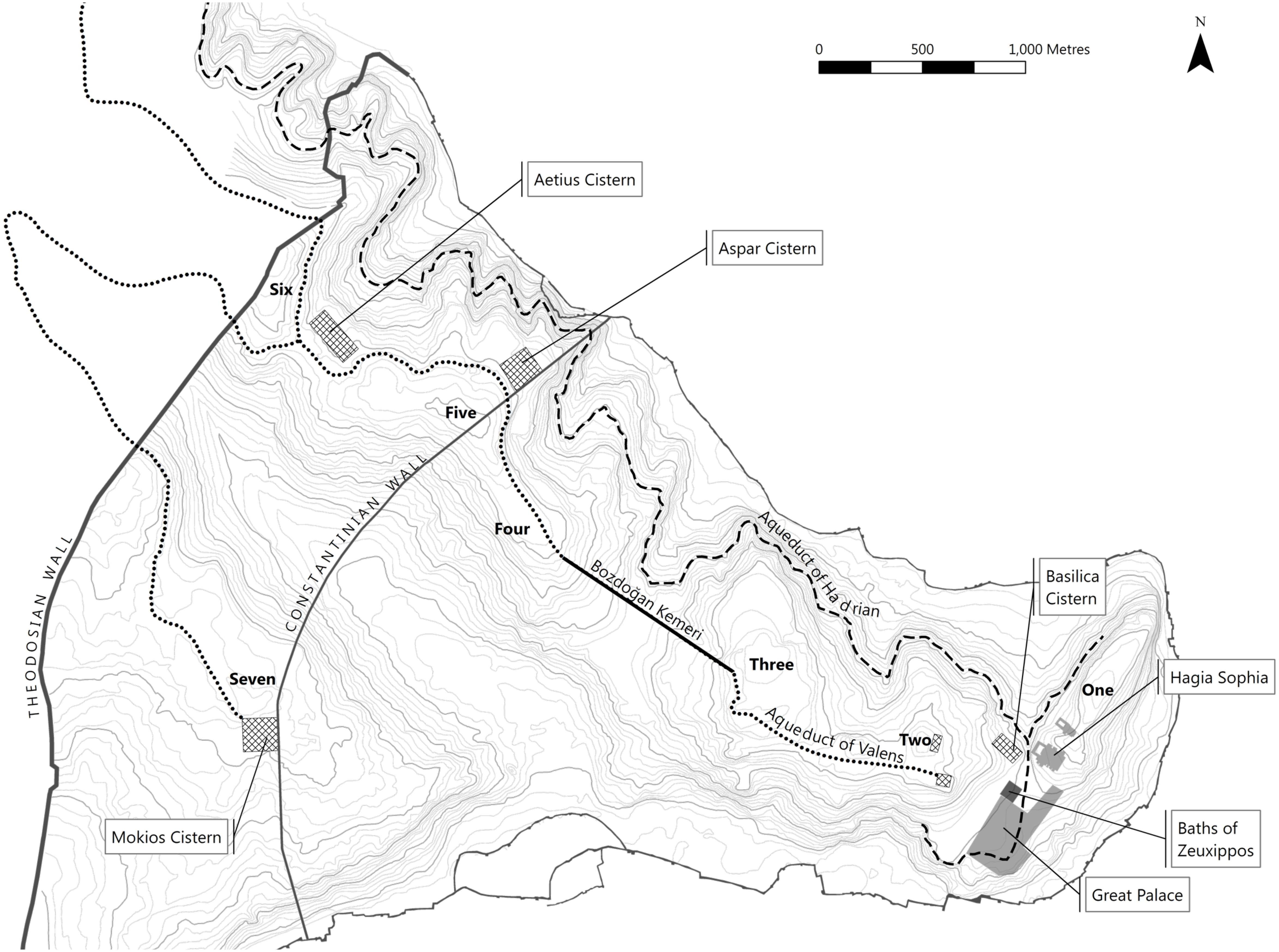
[8] This aqueduct is first mentioned in a law code of the late 4th century where it is referred to as the Aqueduct of Hadrian.



Map 2.2: Topographical context of Constantinople: the seven hills of the city, largest cisterns, key locations and the aqueducts – shown are the routes suggested in Crow, Bardill and Bayliss (2008).

## 2.2.2 The Aqueduct of Valens

Constantinople, larger than Byzantium, was initially bounded by the Constantinian Wall before being extended to the Theodosian Wall constructed in the early 5th century. The city was built on seven hills, six of them forming a ridge on the north side of the peninsula and a seventh, isolated hill on the southern side (see Map 2.2). The development of Constantinople included reclamation of land along the coast and the development of harbours on both the north and south coasts (Mango 2001). The Aqueduct of Hadrian was initially the new city's only water supply, although it may have been augmented by cisterns during the earliest period of Constantinople.[9] However, the expansion of the city soon required another water source at a higher level to serve all areas of the city.

The Aqueduct of Valens is generally agreed to have arrived in the city in 373 (Crow *et al.* 2008, p. 10). After the aqueduct arrived in the city, it was admired and the Emperor Valens highly praised for bringing water into the city whereas Constantine and his son, Constantius II, were admonished for having beautified the city with statues without giving thought to this precious resource:

> *Blessed, Happy Constantine! Do you sense that for you the emperor (Valens) has turned the beloved from an inanimate to an animate state, and that against expectation he has breathed life into this beautiful and desirable body that was still feeble…the city is truly a city and no longer a mere sketch? You and your son were clever in finding for her and giving to her many and manifold girdles and necklaces and bracelets and torques…bedecked with much gold and precious objects she be more thirsty than those who are dressed in rags…*
>
> Themistius, *Oratio* XI.151a (ed. Schenkl, Downey;
> trans. Krausmüller in Crow *et al.*, 2008 p. 224)

It is not clear whether this retrospective scolding is truly warranted. Valens may have been the Emperor when the aqueduct started to deliver water to the city but he certainly did not begin the project. Indeed Themistius, who delivered

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[9] Libanius writes in a letter to Honoratus that the city has "abundant reservoirs". This letter can be dated to around 360-61 which is before the Valens Aqueduct arrived in the city. (Libanius, Letters 251 Bradbury 2004, p.103-105).

this criticism after the Aqueduct of Valens has been completed, provides the earliest reference to the project to bring a new water source to the city some sixteen years earlier in an oration of 357 (Themistius, *Oratio* IV.58bc, cited in Crow *et al.* 2008, p. 223). This, and the estimated construction time of 25 years (Snyder, in preparation) indicate that the project was started in the early period of Constantinople's existence and that the need for water infrastructure must have been a key consideration for early rulers of the city. Other water infrastructure was also being constructed – presumably in anticipation of the arrival of the new aqueduct – including the Baths of Constantianae, which were started in 345 (*Chronicon Pascale* 534 cited in Crow *et al.* 2008, p. 223) and the Modestus cistern, which was begun in 363 (PLRE 1*,* Jones *et al.* 1971, p. 606).

Figure 2.1: The 1km-long Bozdoğan Kemeri: almost all of it remains today. Carrying water across the deep valley between Hill Four and Hill Three, it is the most visible part of the city's ancient water supply. (Photo: S. Smith 2014)

The new aqueduct, now known as the Aqueduct of Valens, was a remarkable feat of engineering, collecting water from two spring sources in Danamandıra and Pınarca. The channel was 215 km long (with an additional branch to

Pınarca) (Crow *et al.* 2008, p. 27) and had gradients typically of less than 0.1%.[10] Critically, this aqueduct arrived at the city at a higher level than the Aqueduct of Hadrian, as shown in Map 2.2. Bringing water to the higher reaches of the area bounded by the Constantinian Wall enabled expansion into these areas, an important requirement for the growing city. The elevation and route of the aqueduct within the city are indicated by the Bozdoğan Kemeri, the aqueduct bridge that allowed water to cross the valley between Hills Three and Four, which, as shown in Figure 2.1, still stands today. The aqueduct followed a route high on the ridge of hills that make up the spine of the city, which would enable water to be delivered to a far greater area than before.

Archaeological fieldwork (reported in Crow *et al.*, 2008) has revealed that this was the first phase of the Aqueduct of Valens. Its arrival saw a rapid increase in the number of large public baths, the *Notitia Urbis* identifying seven that were active by about 425 (Matthews 2012, Mundell Mango 2015, p. 138-140). These baths would have had a considerable water demand[11] and alongside a growing population, may account for the second phase of aqueduct construction identified by the archaeological fieldwork, tapping a source at Pazarlı some 100 km from the city (Crow *et al.* 2008, 27, p. 29-31). Although this second phase is not attested in ancient texts, it must have brought either increased volume or reliability of water to warrant the vast investment it required. There is no clear start or end date for the second phase but with an estimated construction time of 40 years (Snyder, in preparation), planning may have begun soon after the completion of the first phase in 373.

One of the final major expansions to the water supply comes in the early sixth century when the largest of the open-air cisterns, Mokios, was constructed on Hill Seven, known as Xerolophos or the Dry Hill (*Patria* 3.84 cited in Crow *et al.* 2008, p. 231). With the construction of this cistern all areas (except perhaps the highest points adjacent to the Theodosian Wall) could be supplied with water:

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[10] The allowable construction tolerances in modern engineering make constructing such a flat gradient challenging. Typically, larger gravity sewers would be no flatter than 0.25% gradient (1 in 400).

[11] Many Roman Aqueducts were constructed in order to supply public baths (Hodge 2002, p. 6), for example the restoration of the Aqua Marcia and construction of the Aqua Antoniniana for the Baths of Caracalla (DeLaine 1997, p. 16).

the Aqueduct of Hadrian was able to provide water to the lower slopes on the north side of the peninsula; the Aqueduct of Valens to both slopes of the ridge made up of Hills One to Six; and the Mokios cistern to Hill Seven. The water source for Mokios is unknown, although Crow *et al.* (2008, p. 132) suggest that it may have been fed from a branch off the Aqueduct of Valens (illustrated in Map 2.2). This branch in the early sixth century may have been the final piece of infrastructure constructed to bring water into the city, but inside the city's walls investment in infrastructure to store and distribute water continued from the earliest period until the 15th century.

### 2.2.3 Cisterns

Although cisterns had been a common water supply technology since prehistoric times (Mays, Antoniou & Angelakis, 2013), in Constantinople they reach unprecedented scale and complexity, apparently being combined in a network to manage the city's limited water resources. The first mention of cisterns in Constantinople is in a letter written by Libanius before the arrival of the Aqueduct of Valens (Letters 251, trans. Bradbury 2004 p. 103-5). So at a time when a growing city was having to manage on the water supply of a (presumably much) smaller community, one of the technologies it employed was the cistern. Next, and still before the arrival of the Aqueduct of Valens, the Modestus cistern was constructed in 363 (PLRE 1, Jones *et al.* 1971, p. 606). This cistern has now been lost but it could be the first of the large open-air cisterns as it is associated with the description, by Gilles, of the remains of a cistern housing 200 saddle-making workshops and stalls close to the Bozdoğan Kemeri (Byrd 2008, p. 178) (Crow *et al.* 2008, p. 123) and it was sufficiently significant to be included in the list of assets given by the *Notitia Urbis* (Matthews 2012, p. 94).

The construction of the second phase of the Aqueduct of Valens also marked the beginning of a series of major cistern-building periods. In the early to mid 5th century five large cisterns are known to have been constructed, including, on the periphery of the city, two of the largest: Aspar and Aetius. More centrally, the Theodosian and Arcadiaca cisterns, which, as they are recorded in the *Notitia Urbis*, were presumably large and perhaps also open-air (Matthews 2012, p.89 &

94). A second wave of cistern-building occurs in the early-6th century, including the largest open-air cistern, Mokios, in either 499/500 or 514/515 (Crow *et al.* 2008, p. 132), and the largest covered cistern, the Basilica cistern, in 527 and also possibly the Binbirdirek cistern in the same period (Crow *et al.* 2008, p. 123). The Justinianic plague devastated the population in the mid to late 6th century but was followed by another wave of major cistern construction in the late 6th and early 7th century, including the cistern at the Bronze Tetrapylon, the cistern of Bonus and the cistern at *ta Armatiou,* although the precise location of these cisterns is no longer known (Crow *et al.* 2008, p. 128).

### 2.2.4 Cistern purpose

There is no definitive answer as to why cisterns played such a key role in Constantinople's water supply. The rationale for constructing the Basilica cistern is given by Procopius as addressing summer shortages.

> *In the summer season the imperial city used to suffer from scarcity of water as a general thing, though at the other seasons it enjoyed a sufficiency…the Emperor Justinian made a suitable storage reservoir for the summer season, to contain the water which had been wasted because of its very abundance during the other seasons…*
>
> Procopius *Buildings* 1.xi.10-15
> (Dewing and Downey 1940, 91)

This may be the reason for all the cisterns in Constantinople, although it is worth noting that at the time of the construction of the Basilica cistern, there was already a considerable amount of water storage within the city, largely in the Mokios, Aetius and Aspar reservoirs (along with the unknown but significant volumes of the Modestus, Arcadiaca and Theodosius cisterns). It is possible that the water in open-air cisterns was not used for drinking (although in times of scarcity, all available water sources are likely to be exploited) or merely that the location of these cisterns, on the periphery of the city, made the water less accessible.

Security is a possible driver for the reliance on cisterns, as water stored in cisterns would allow the city to continue in the event of the external water supply being cut off, making it more resilient during a siege. There are two recorded instances of the water supply being tampered with, firstly for a brief period in the late 5th century by Theodoric Strabo, who was familiar with Constantinople's infrastructure (Malalas, Chronicle 15.9 trans. Jeffreys *et al.* 1986), and secondly during the Avar siege of the city in the early 7th century. This time the interruption to the water supply was considerably longer than a few days: the Aqueduct of Valens is reported to have been repaired in 765, 140 years after the Avar siege (Theophanes *Chronicle* AM 6258, trans. Mango & Scott 1997). Since life continued in the city, the Avars clearly did not cut both the aqueducts (see discussion in Crow *et al.* 2008, p.19-20). The population was able to survive well enough on the water available from the Aqueduct of Hadrian although only having water at this lower elevation would have curtailed activities in many areas of the city.

### 2.2.5 The end of the water supply

Visitors to the city reported a functioning water system up to the mid-12th century – William of Malmesbury, visiting in the late-11th century, recounts the common misconception that Constantinople's water was transported all the way from the Danube, and Odo of Deuil in c.1150 reports that the city had an "abundance of sweet water" from "outside underground conduits" (*Gesta Regum Anglorum* trans. Mynors *et al.* (1998) & *De profectione Ludovici VII in Orientem*, trans. Van der Vin (1980) cited in Crow *et al.* 2008, p. 238-9) but around this time some of the bridges outside the city appear to have deteriorated beyond repair – by the late 12th century the "old arcades which conveyed water to Byzantion were long since collapsed" (Kinnamos, trans. Brand 1976, p. 205-6). However, although this may have marked the end of the city being supplied by the Roman world's longest aqueduct, the system within the city appears to have still been in use – water is reported to cross the Bozdoğan Kemeri in the 15th century (Clavijo trans. Le Strange 2005 p. 88) – so an alternative water source closer to the city may have been harnessed and the Aqueduct of Hadrian may still have been in use.

Following the Ottoman conquest in 1453, the city, including the water supply, underwent significant changes. Initially the Ottomans probably used much of the same water supply infrastructure but this was gradually replaced by aqueducts from two main sources – the Kırkçeşme system, which took water from the Belgrad Forest, and the Halkalı system that comprised multiple channels collecting from many small dispersed springs in the Halkalı area some 12 km from the city (Çeçen 1991, Plan 9). This marked the end of the water supply of Byzantine Constantinople although elements of it, including the Bozdoğan Kemeri and Basilica cistern, continued to serve the city as part of the Ottoman water supply.

## 2.3 The physical evidence

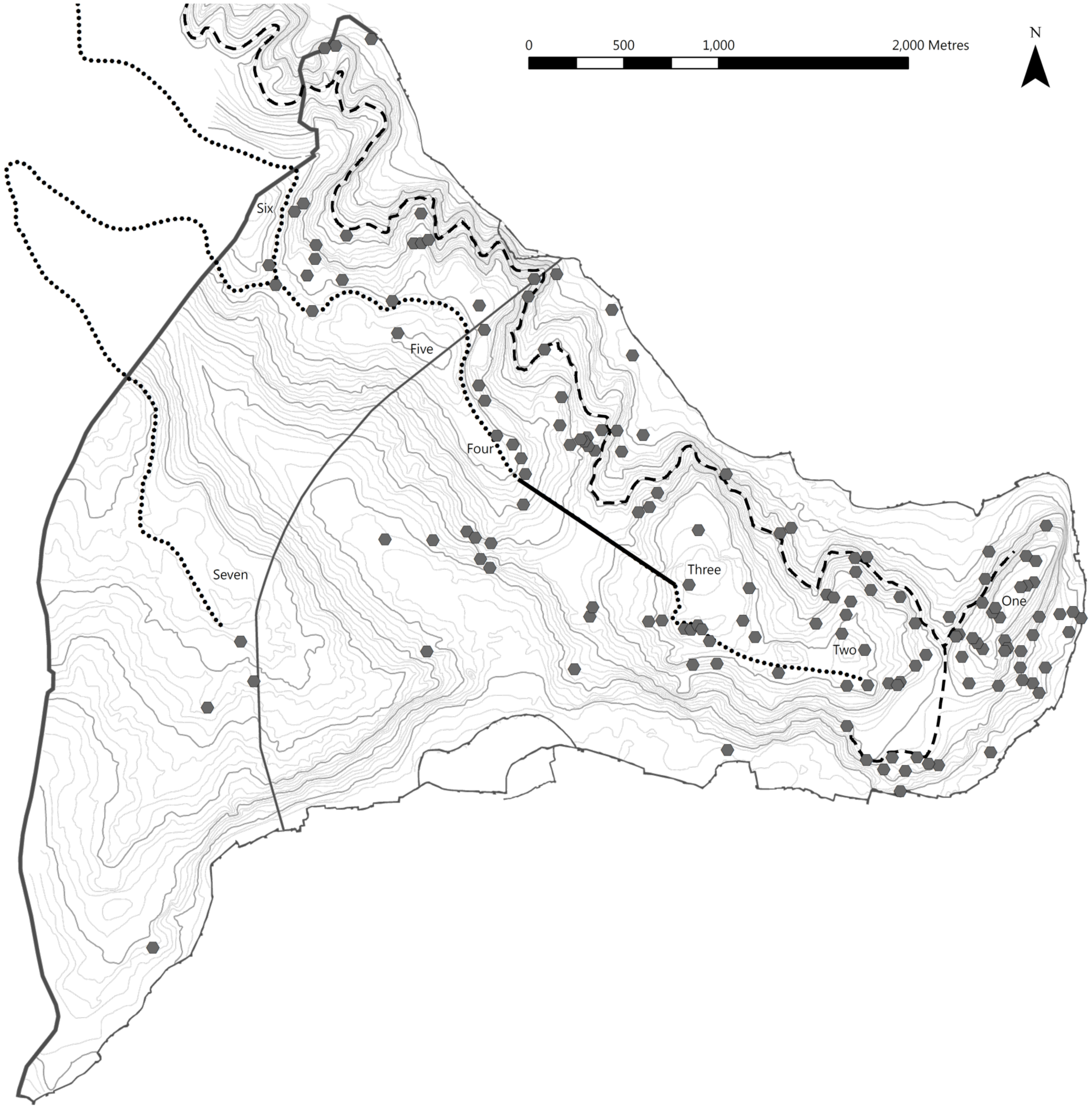
This section outlines the understanding of the physical evidence prior to the present study – the baseline data on which this study was based. Section 2.2 provided a historical and topographical account of the water supply that will serve as a framework for understanding the detailed investigations into the water supply system. Although the water supply has rarely been considered as a whole, working system, many have studied the elements of the system in detail. This is particularly true of the cisterns, which have been reported, recorded and mapped since the visit to Constantinople by Pierre Gilles in the mid 16th century. Apart from the Bozdoğan Kemeri, which was investigated in detail by Dalman (1933), channels and pipes have not been the focus of much work and are usually reported on incidentally in other works. During the course of the study the understanding of the physical evidence has developed, particularly with regards to the number of cisterns known in Constantinople and the routes of the aqueducts within the city. The results of this work are presented in Chapter Six.

### 2.3.1 Cisterns

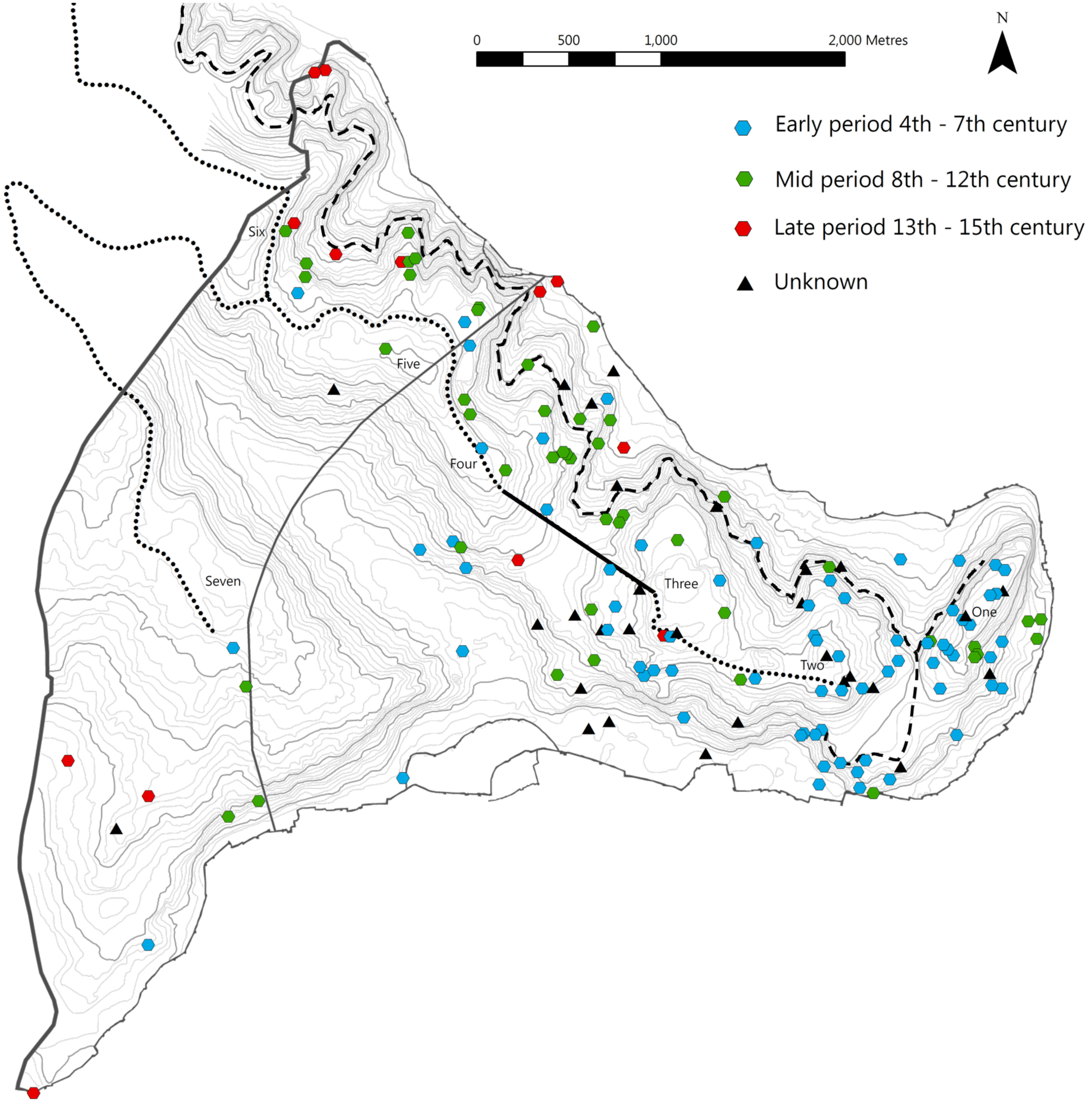
Since the rediscovery of the Basilica cistern described in Chapter One, scholars have discovered and reported on cisterns beneath Constantinople, and the number of cisterns known has grown substantially. Gilles' writings on Constantinople include brief descriptions of eight cisterns he was able to visit (trans. Byrd 2008, p. 101, 111, 156, 178-9, 189-90) and at least one, the Basilica cistern, was still in use in the mid 16th century. Forchheimer and Strzygowski (1893) compiled the first catalogue of cisterns within the city. Their catalogue identifies four uncovered cisterns (Mokios, Aspar, Aetius and the Fildamı, which lies outside the city walls), 40 covered cisterns and reported descriptions of 27 sites that they were unable to access and confirm. For each of the cisterns visited there is a description of how to find the cistern along with a brief description and plan with dimensions and occasional sketches of architectural details. Although cisterns were not the main focus of the Müller-Wiener (1977) study of the topography and remains of Byzantine and Ottoman Constantinople, it does map about 75 cisterns. Tezcan (1989) investigated the Topkapı Palace area and found at least 27 Byzantine era cisterns in the vicinity of Hill One along with a number of Ottoman water structures that are suspected to have Byzantine origins.

The two most recent and comprehensive studies have confirmed a large increase in the number of Byzantine cisterns, more than doubling previous totals, showing that they were widespread across the city. A bibliographical concordance, assembled by Bardill in Crow *et al.* (2008, p. 145–155) lists 161 cisterns known from the literature and, where possible, maps the location, adopting the numbering scheme used by Müller-Wiener. The cisterns included in this concordance are shown in Map 2.3. Although cisterns are present all over the city some areas are more densely populated than others, with the area around Hill One particularly densely populated. Map 2.4, illustrates the findings of the most recent work, a catalogue by Altuğ (2013) listing 158 cisterns. This catalogue offers a different perspective, mapping only cisterns for which physical remains or firm records of location were available. With access to the Istanbul Municipality records, Altuğ was able to add a number of cisterns not published in academic literature, which, in some cases, are in areas where Bardill's concordance had few cisterns. Altuğ also demarcates cisterns by date, into three time periods: early (4–7th centuries), mid (8–12th centuries), late (13–15th centuries) and a fourth unknown era category. Altuğ's dating convention is reproduced in Map 2.4 illustrating that although the early period saw the greatest period of cistern building, cisterns kept being added to the water supply system, at a declining rate, throughout the era of Byzantine Constantinople.

The key point to draw from these two studies is uncertainty – there is a lack of clarity on the total number of cisterns, the construction dates for a significant proportion are unknown and there is almost no information about how long cisterns were used for and when they stopped being operational. The two recent studies (Crow *et al.* 2008 & Altuğ 2013) report approximately the same number of cisterns, using two distinct approaches, but closer inspection reveals that the cisterns listed do not match; this anomaly is resolved in Chapter Six. We also do not know whether these two studies cover all the cisterns that were present in Byzantine Constantinople, although this seems improbable. Yet finding more cisterns is also unlikely, as both Ottoman Constantinople and modern Istanbul have continually built on top of the Byzantine city.



Map 2.3: Location of 149 of the 161 cisterns listed in Crow, Bardill and Bayliss (2008). Of the twelve remaining cisterns, two are located on the Galata peninsula, three have been identified as double entries and the remainder do not have a firm enough location to plot on the map.



Map 2.4: The locations of the 159 cisterns included in Altuğ (2013). Organised by date of construction: early 4–7th century; mid 8–12th century; late 13–15th century; unknown period.

It is perhaps unsurprising that the area most densely populated with cisterns is on Hill One, which has been protected from extensive development by the Topkapı Palace.

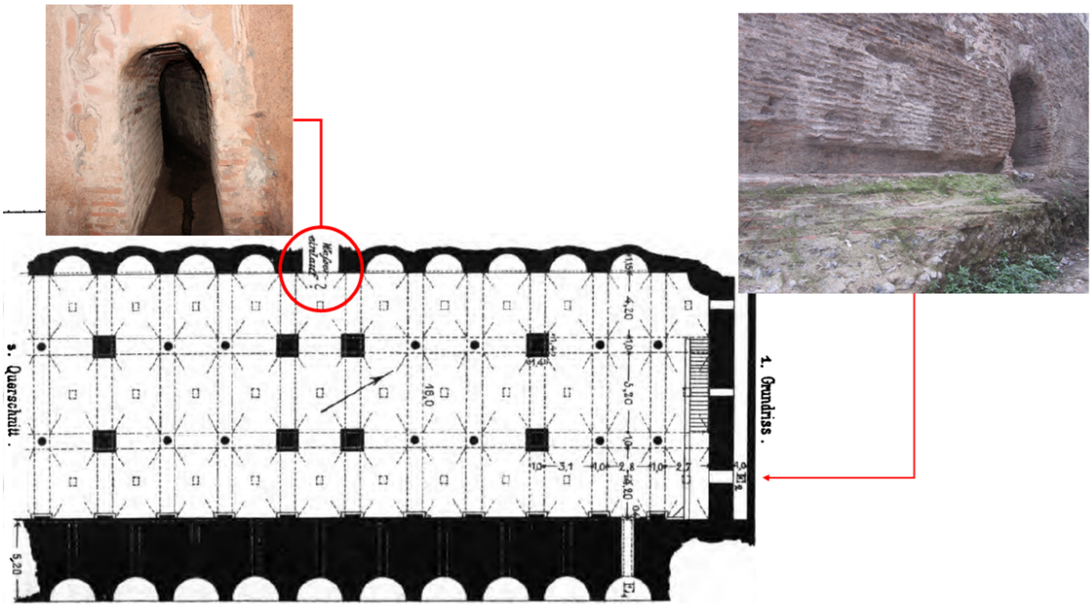


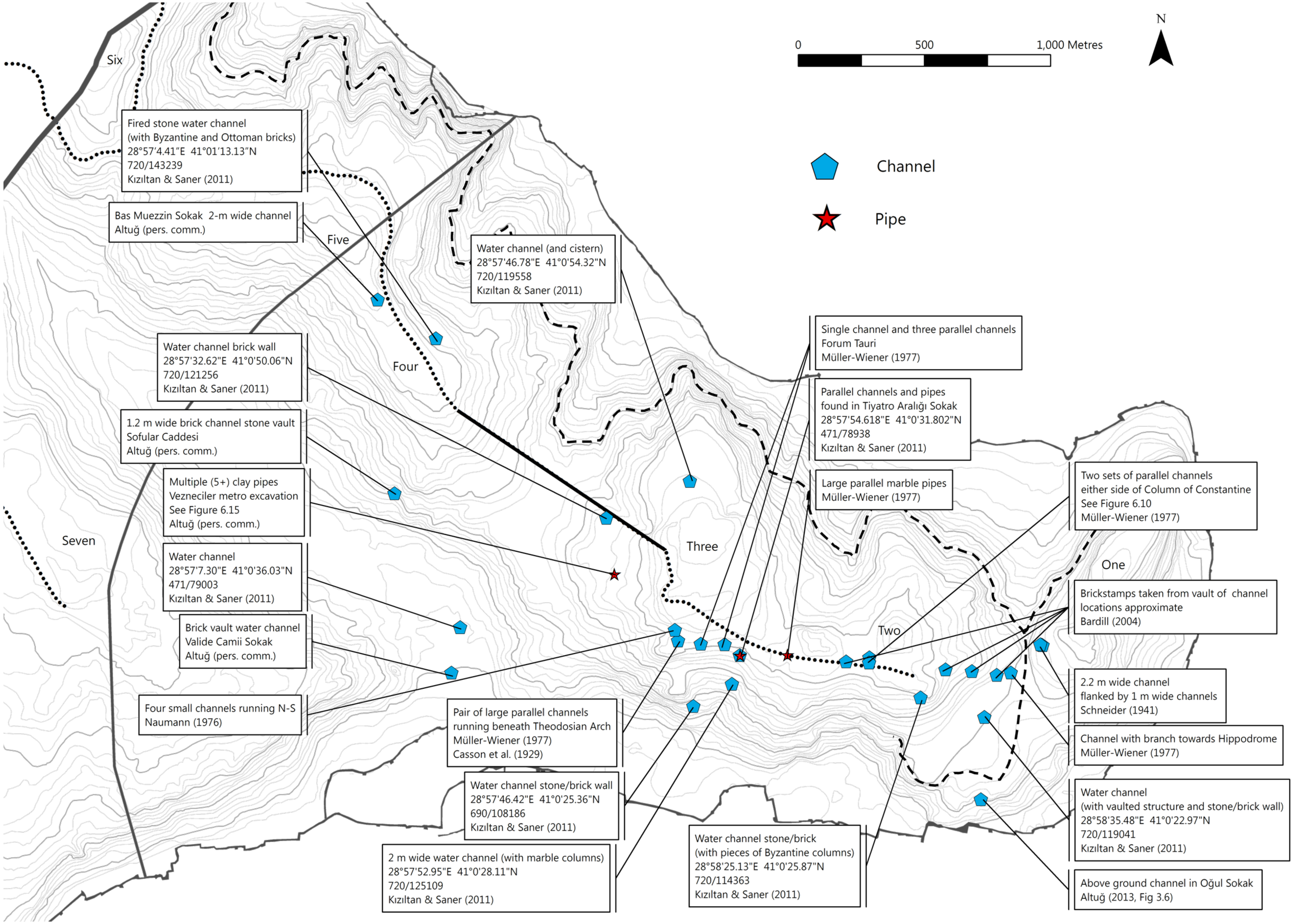
Figure 2.2: Unkapanı cistern plan (Forchheimer & Strzygowski 1893) and photographs of the two openings.

There is also relatively little detail available on how the cisterns operated. For most cisterns there is no information on how water entered or was extracted. For many of the best preserved cisterns, later alterations have obscured inlets and outlets. For example, when Gilles (trans. Byrd 2008, p. 101) is exploring the Basilica cistern in the 16th century, he describes water pouring into the cistern from a large pipe but today there is no indication of where the pipe entered the cistern. It may have been lost during renovations to make the cistern accessible in the 1980s or it may have been in the walled-off section that collapsed at some point in the past. Such lack of detail is a significant challenge in understanding how the network was connected and controlled. However, there are a few exceptions, such as the Unkapanı cistern, where two openings (Figure 2.2) offer some clues about how the cistern operated.

### 2.3.2 Channels within the city

Water was distributed to the many cisterns across the city but there is little evidence of how this was done. Work on the aqueducts has focused on the routes outside the city, where it is possible to find and trace the channels (primarily Çeçen 1996a and Crow *et al.* 2008). Within the city walls there has been no comprehensive work on tracing and mapping channels but there are a number of reports and studies which identify channels and pipes at various locations across the city. These findings range from the 2.5 m high, 1.6 m wide double channels found next to the Column of Constantine (Mamboury 1936, p. 254) to large diameter (approx. 300 mm) carved stone pipes (see Figure 2.3), to multiple smaller clay pipelines excavated during construction of the Vezneciler Metro station (pers. comm. K. Altuğ, see Figure 6.15). Of the 30 channel/pipe observations in Map 2.5, nine are from the Istanbul Archaeological Museum Archive (Kızıltan & Saner 2011) which provides only coordinates and an extremely brief description, the remainder have either a sketch or photograph associated with the findings. Only three of these observations are of pipes, although it is likely that pipes were a common technology within the city.

Figure 2.3: Carved stone water pipe in the grounds of the Hagia Sophia (K Ward)



Map 2.5: Byzantine channel and pipe fragments found within the city

### The Aqueducts

The only physical evidence of the 2nd century aqueduct are indications of earlier structures within some of the Ottoman-era bridges on the Kırkçeşme system outside the city (Tursun Bey and Gilles both cited in Crow *et al* 2008, p. 242-3). From this it is believed that the Kırkçeşme, which tapped sources in the Belgrad Forest to the north of the city, used the same route as the Roman aqueduct and might reasonably be used as a proxy for the older system. Inside the city there is speculation that a structure associated with the Kırkçeşme system, the Tezgahçılar distribution chamber, was originally Roman and converted by the Ottomans (Çeçen 1996a, p. 155). There is no other physical evidence associated with the Aqueduct of Hadrian, so the study of this element of the system relies on textual evidence and interpretation of topographic data.

There is more evidence of the Aqueduct of Valens than the Aqueduct of Hadrian, both inside and outside the city. The line of the aqueduct outside the city is detailed in Crow *et al.* (2008) and is being refined further by the work of Ruggeri (2018 PhD), conducted parallel to this study. Within the city the clearest evidence of the Aqueduct of Valens is the monumental bridge, called the Bozdoğan Kemeri in Turkish, which as discussed above, still stands in the city today (see Figure 2.1). Channels and stone pipes have been found at a number of points along the Mese, the main street in Constantinople connecting Forum Tauri, the Forum of Constantine and the Augusteon outside the Hagia Sophia. However it is not certain if these artefacts belong to the water system or the drainage system.

One study, focused on channels associated with the Hagia Sophia, reveals a density and complexity of channels that may have been common throughout Byzantine Constantinople. Özkan Aygün (2010), using caving and scuba diving techniques, explored the network of channels and cisterns beneath the Hagia Sophia and Topkapı Palace and was able to map seven different channels totalling 1 km beneath the Hagia Sophia and its grounds. Unfortunately further exploration of the channels was curtailed both by channel collapses making some routes inaccessible and the formidable bureaucratic constraints in obtaining permission for access.

## 2.4 Textual Sources

Much of the evidence of the water supply in Constantinople comes from textual sources. Three types of textual sources are discussed in greater depth here: the Law codes of Theodosius and Justinian, which record several laws pertinent to aqueducts and water supply, the *Notitia Urbis*, a document describing the city and its assets in the early 5th century, and other texts, mostly contemporary histories, accounts and orations.

### 2.4.1 The Law codes

The Theodosian and Justinianic Law Codes provide some of the key textual evidence for the first two centuries of Constantinople's water supply. From these two sources we can get insights into water use; water misuse and corruption; some high-level water management techniques; and evidence of aqueduct restoration in the late 4th century and construction in the late 5th century. Some laws apply directly to Constantinople whilst others are specifically for other locations but can also be considered relevant and instructive of how the authorities organised and managed water resources.

#### Water use

The law provides glimpses of what aqueduct water was used for, often when prohibiting or limiting that specific use. In this way, we learn that water was taken for irrigation use on farms, fields and gardens; for industrial use in mills; for bathing in both private and public baths, and to supply private dwellings and country villas as well as the public supplies to fountains (*Cod. Theo*. 15.2.3, trans. Pharr 1969, *Cod. Just* 11.43.5, 11.43.6, 11.42.10, trans. Frier *et al.* 2016).

#### Misuse and corruption

A fairly constant thread through the water-related laws is the inappropriate use of water. In the late 4th century laws address issues of people taking water directly from the aqueduct rather than a reservoir and from the public aqueduct for their own farm use, as well as admonishments for people trying to obtain permission for the right to use water from an inappropriate official and for continuing to take water from the public supply when that right has been uniformly revoked (*Cod. Just.* 11.43.2, 11.43.5 and *Cod. Theo.* 15.2.6). By the late 5th century there appear to be problems with people interfering with public infrastructure – converting public fountains to private use and interfering with the smaller aqueducts that were fed by public fountains (*Cod. Just.* 11.42.9, 11.42.10). More sinisterly, there are a number of laws which appear to try and counter official corruption, with laws claiming officials, including urban prefects, interfered with publicly-constructed aqueducts and diverted money associated with their construction or maintenance (*Cod. Just.* 8.13.1, 11.42.8)

### High level management

Many of the management measures provided by the law are about controlling the right to draw water. Permission to draw water from the public supply could only be issued in writing by the Emperor and this further registered with the Urban Prefect. Given the laws about recovering public water from private hands, it is clear that the law for acquiring permission to draw water was bypassed many times. The financial repercussions of taking water were quite severe, with the perpetrators forfeiting land to the privy purse or paying a substantial fine (*Cod. Theo.* 15.2.6, *Cod. Just.* 11.42.6).

At the end of the 4th century there is a clear management decision to limit the use of water from the Aqueduct of Hadrian to the fountains of the Imperial Palace, the public baths (these are taken to be the Baths of Achilles, ancient baths which may predate Constantinople, although there is some ambiguity in the text which suggests that it may be the Achilles baths and some other baths (most likely the Zeuxippos baths)) and, possibly, public fountains (*Cod. Just.* 11.42.6, trans. Frier *et al.*2016).

More specific management is given in one of the earliest laws relating to water, dated 382, which sets out the appropriate size for private connections to the public supply. These vary from a half-inch to a 3 inch pipe[12] depending on the rank of the householder and the presence and size of baths being supplied (*Cod. Theo.* 15.2.3, trans. Pharr 1969). The responsibility for allocating water between baths, public fountains and private citizens is discussed in *Cod. Just.* 11.42.5 (trans. Frier *et al.* 2016). Although this law refers to a provincial governor so is

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[12] I have maintained the imperial units used in the translation rather than convert to metric units.

not directly applicable to Constantinople, it is relevant that the law code details such decisions on allocation. The law code also gives a glimpse of the workforce associated with the water supply: a late-5th century law from the Emperor Zeno gives details of *hydrophylaces* who were the "inspectors and guardians of water" and were branded as such with a mark borne on the hand (*Cod. Just.* 11.42.10, trans. Frier *et al.* 2016).

### Aqueduct construction

In laws of the late 4th century there are several references to manpower being required and funds diverted variously to the restoration of the Theodosian Aqueduct, "the repair of the aqueducts of this renowned city" and "the construction and repair of the aqueduct" (*Cod. Just.* 11.42.7 and *Cod. Theo.* 15.1.23). At this point in time the city is supplied by the Aqueduct of Hadrian and the recently completed first phase of the Aqueduct of Valens. It is not clear which aqueduct is being referred to as the "Theodosian Aqueduct". The second phase of the Aqueduct of Valens may be underway, but Crow *et al.* (2008, p. 16) identify the financial contributions being made as too small for this enormous undertaking. Additionally, a law of 396 (*Cod. Theo.* 6.4.29, trans. Pharr 1969) rescinds the requirement for "theatrical expenditures to be diverted to the construction and repair of the aqueduct" so the need for money at that point has ended or been reduced considerably, which does not match the expected 40 year construction period and the mid-5th century construction style seen in some of the second phase bridges. Given that the first phase of the Aqueduct of Valens was only a few decades old at this point it is valid to conclude that the work is being done on the Aqueduct of Hadrian (see Crow *et al.* 2008, p. 16). The new title and the use of the word "construction" alongside "repair" may imply that the Aqueduct of Hadrian was being modified and extended rather than just returned to fully operational status. It would also make practical sense that the city would first secure another water source (the Aqueduct of Valens) before undertaking major works on the Aqueduct of Hadrian.

There are suggestions in the law codes that there was also aqueduct construction being undertaken in the late-5th century. Two laws from Emperor Zeno (*Cod. Just.* 11.42.8 & 11.42.10, trans. Frier *et al.* 2016) that relate to anti-corruption measures mention money for the construction of aqueducts. It is not clear where these aqueducts are as the time period is too late for the second phase of the Aqueduct of Valens. One possibility is that they relate to an aqueduct to feed the Mokios cistern on Hill Seven but since the date of the cistern is thought to be either 499/500 or 514/515 (Crow *et al.* 2008, p. 132) the aqueduct construction may be too early. The second possibility is that "aqueduct construction" refers to smaller aqueducts within the city.

### 2.4.2 *Notitia Urbis Constantinopolitanae*

The *Notitia Urbis* offers a snapshot inventory of the city in about 425 (Matthews 2012). In describing the geography of its regions and listing the infrastructure and significant elements found in each, the *Notitia Urbis* provides us with one of the clearest and most comprehensive views of the Byzantine city. It enumerates 14 regions, of which two are outside the main peninsula. The remaining twelve describe the city up to the Constantinian Wall, that is, excluding the area between this Wall and the Theodosian Wall, as illustrated in Map 2.6.

There are a relatively small number of water-related entries, with two nymphaea (large public water fountains) in regions IV and V and the Greater Nymphaeum in Region X along with three named cisterns.[13] Some major water users are also identified, with seven public baths and 153 private baths in Regions I to XII along with indications of commerce and industry with numbers given for private and public bakeries and the names of significant warehouses.

Although the *Notitia Urbis* contains a wealth of information, care must be used when interpreting the figures given. For example, the number of *domi* – houses – is provided for each region, with a total of 4,388 across all the 14 regions. Anderson (2016) uses the *domus* as a proxy, not strictly for population distribution, but as a density of domestic building. However to make this viable, given that the population of Constantinople was at least several hundred thousand, he makes an assumption based on the figures given for Rome in a document that predates the *Notitia Urbis* by at least a century. This document uses two terms to describe domestic dwellings: the *domus,* of which there are 1,790 in Rome, and *insulae,* considered to be units within multiple households

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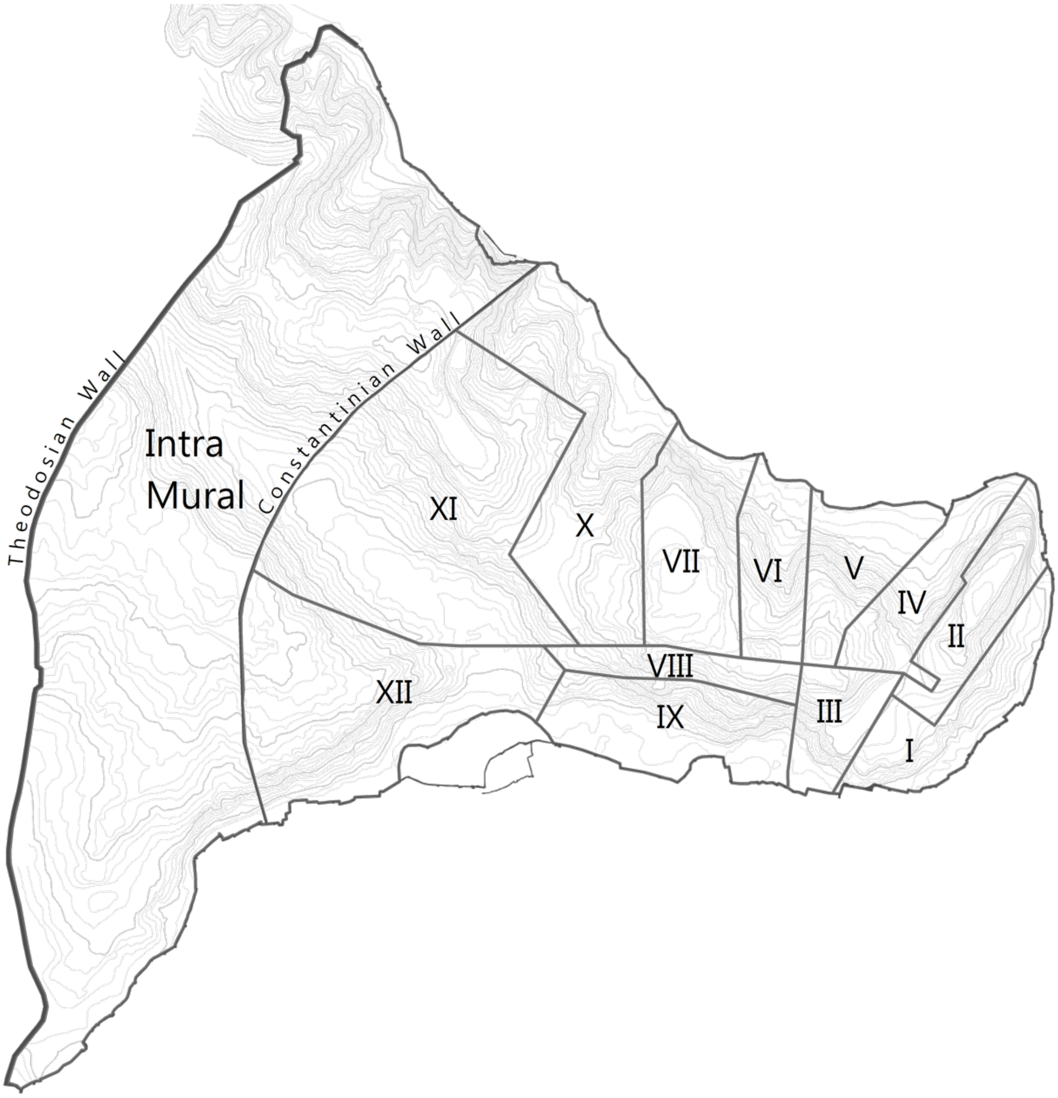
[13] Although the tally given in the document says that there are four cisterns.

*i.e.* single residences making up a tenement block. There are 46,602 listed for Rome; the term *insulae* is not used in *Notitia Urbis* but Anderson assigns 2,598 of Constantinople's 4,388 *domus* as tenement blocks containing 23,000 *insulae* (half the figure for Rome) and the remaining 1,790 *domus* as houses in the same sense as Rome's term *domus*. These figures appear, on the surface, to be reasonable; however they are founded on arbitrary assumptions about the comprehensiveness of the *Notitia Urbis* and the ways in which Rome can be compared to Constantinople. We must be careful of the reliance we place on the figures they produce.



Map 2.6: Approximate regional boundaries of the city as defined by the *Notitia Urbis*

Despite this cautionary note, the *Notitia Urbis* is undoubtedly useful. By providing a geographical description of each region, it is possible to locate specific facilities in particular areas of the city. This information can be considered in combination with the physical evidence on cisterns when developing the possible routes of the water network. For example, the information on water users, such as public and private baths, can indicate the presence of the water network when other evidence is lacking. The number of cisterns now discovered is higher than ever but it would be naive to conclude that all the cisterns of Constantinople have been found. There are still areas such as Region IX where there are very few cisterns, but the presence of a public bath and 16 private baths strongly suggest the water supply also operated here. The spatial information provided in the *Notitia Urbis* gives a granularity that is important when considering the details of the water supply and as discussed in Chapter Five allows the distribution of water demand to be considered.

### 2.4.3 Other ancient texts

The evidence from the histories, accounts and orations, although not as dependable as evidence from the law codes and Notitia Urbis, provides a different perspective on the water supply. Many of the accounts heap a huge amount of praise on the water supply, with the "abundance of water" it provided being a common theme (for example, Themistius, *Oratio* XIV.183b-184a cited in Crow *et al.* 2008, p.226). However, it is also in these accounts that the other side of the water supply becomes visible; indications that the municipal authorities were not always able to meet the water requirements of the population. Malalas, writing a contemporary account, describes fights breaking out around cisterns during severe drought (Malalas, Chronicle 18.139, trans. Jeffreys *et al.* 1986). Procopius, another contemporary historian, reports on a period when the aqueducts had been so neglected that it led to a reduction in flow arriving in the city and a time of water stress for the inhabitants of the city:

> *"...a great throng of the people, bursting with indignation, was always gathered at the fountains, and that all the baths had been closed"*
>
> (Procopius, *The Secret History*, 26.23 trans. Dewing 1935, 311).

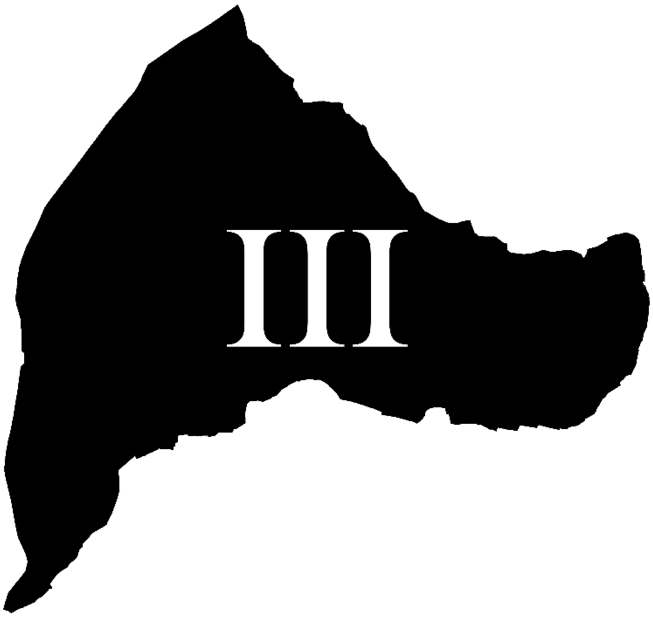
During the period when the Aqueduct of Valens was cut off (626–765), Theophanes provides evidence that the aqueduct was indeed dry, describing how the Emperor Justinian II was able to use it as a secret route into the city during a period of rebellion, (Theophanes, *Chronicle* AM 6197, trans. Mango & Scott 1997) and that many cisterns were out of commission, reporting that a plague in 747/8 was so severe that the number of dead bodies exceeded the capacity of the cemeteries so that they had to be placed in empty cisterns (Theophanes, *Chronicle* AM 6238, trans. Mango & Scott 1997). However, the cisterns were presumably cleared out shortly after as they were brought back into use as water storage when the Aqueduct of Valens was repaired in 765/6, a task that required about 7000 labourers from across the Empire (Theophanes, *Chronicle* AM 6258, trans. Mango & Scott 1997). The repair of the Aqueduct of Valens was prompted by a period of drought that resulted in empty cisterns and baths – enough to tell us that up to that point the Aqueduct of Hadrian was able to sustain a successful capital city albeit one that had a population much reduced by plague (and therefore less demand for water).

## 2.5 Summary

The representation of the water supply given in this chapter incorporates a range of disparate data to create a high-level overview of the water supply system. The city initially relied on the Aqueduct of Hadrian, constructed to serve Byzantium 200 years before the inauguration of Constantinople. It then added additional water resources and capability to serve the higher areas of the city with the two phases of the Aqueduct of Valens. At that point, the focus of water infrastructure moved to construction of cisterns inside the city's defensive wall. Over the millennium that the water supply was used, it developed into a complex and sophisticated network that, unusually for the Roman world, turned to storage and management rather than building more aqueducts as a means of satisfying the water needs of the growing city. Central to this storage approach is the cistern, which is widespread across the city at a range of scales. However, the picture of the water supply is far from complete and the limitations of what is known become clear when looking at the system in more detail. The lack of detailed data make in-depth analyses of the system and its elements challenging.

# Going with the flow: a review of ancient water technology

The development of the cistern from residential rainwater harvesting
to municipal storage and distribution – how other ancient settlements
approached water supply – previous examples of the engineering
approach in archaeological water supply



## III

## 3.1 Introduction

Like many long-inhabited cities, Istanbul is built upon the layers of previous settlements. It is a crowded, flourishing city, home to at least 15 million people, where although construction has been continual, the modern occasionally makes space for the remains of both Byzantine and Ottoman Constantinople. A pile of carved stones on the pavement next to a busy road carrying four lanes of traffic and two tram lines is all that remains of the triumphal Arch of Theodosius (see Figure 3.1) that once crossed the Mese, the main road into the heart of Constantinople. This arch, at least, is visible; much of the rest of the ancient city is buried up to five metres below the modern streets (see discussion of Byzantine ground levels in Section 5.2.1 and Crow *et al.* 2008, p. 110).

Figure 3.1: The remains of the Arch of Theodosius at modern street level.

Development and construction makes it difficult to rigorously study and explore the remains of the water system because so much is covered and inaccessible. However, paradoxically, it is also construction that offers the best chance of making new discoveries, as shown with the recent example of an early Byzantine street (complete with multiple terracotta water pipelines) uncovered during the excavations for the Vezneciler Metro station (K Altuğ pers. comm.

see Figure 6.15). Such findings are serendipitous and constrained by the boundaries of the site, and also often by the time available to study them. These glimpses of primary evidence of the water supply are important but do not offer a realistic or rigorous way of studying it.

Rather than relying only on chance findings in Istanbul, we need look to a wider pool of information. For instance, an informed consideration of both contemporary technology and how it was deployed in other sites across the Roman Empire could shed light on what was done in Constantinople. A fundamental characteristic of civil engineering, now as in Roman times, is that it is defined by the physical context in which it operates: each solution is shaped by the specific environment of the site. Where the sites have not been radically altered, the perspective of the modern civil engineer will be the same as her Roman counterpart. If we couple this with an understanding of the technology of the times, we might fill in some of the gaps in our present understanding.

The previous chapter established that the cistern is a key technology in Constantinople's water supply, so studying its development and use in general can assist in understanding how it was used in Constantinople. Cisterns were used across the Mediterranean from the Bronze Age (Mays 2014), typically on a small domestic scale but by the Roman period the technology available allowed an increase in scale and sophistication culminating in the cisterns of the Byzantine period. Although the cistern is important, it is only an element: we also need to consider the system of which it was a part and contemporary water supply systems generally.

All settlements of significant size have to consider how to supply enough water for their inhabitants. In addition to the physical context of the site, each settlement's solution was dependent on the availability of resources and technology, as well as the expectations of the population. By considering what has been discovered and studied in a selection of ancient urban centres: Pompeii, Ephesus, Carthage, Barcino, Petra, Thessaloniki and Rome, along with briefer insights from a number of other places, it is possible to build a picture of the typical problems faced and the solutions employed in supplying water in the Roman and Late Antique periods.

Engineers have engaged with archaeological evidence before, although they have rarely attempted to use their engineering skills to bridge the gaps where data is lacking. Instead, their work has largely focused on understanding the operation of isolated pieces of infrastructure which afford sufficient data for computational analysis. By reviewing this work we can benefit from what they have established but also discuss how we might widen the scope and use engineering expertise to see these elements not in isolation but as part of a system.

## 3.2 Cisterns

The cistern is a relatively basic technology – it is a structure assigned to the storage of water. Having said that, there is a great deal of variety and development visible in the archaeological evidence: what existed in the Bronze Age as a small rock-cut hole in the ground for holding surface runoff had, by the sixth century, developed into multi-pillared, brick-vaulted structures, capable of holding enough water for an entire city. To understand the many cisterns of Constantinople, we will track the development of the cistern from the Bronze Age in Greece and the Near East, studying how improvements in building technology allowed the cistern to increase in size from a domestic to a municipal technology and enabled improved water quality, freedom to provide for high volume water users and, ultimately, a major change in function, as seen in Constantinople's network of cisterns.

### 3.2.1 Size and building technology

The purpose of a cistern is to fill up quickly when water is available and empty more slowly, according to the needs of the users. The size of a cistern is dependent on its function and the availability of water. The volume of water to be stored will depend on the length of time a cistern needs to serve the user before being refilled. For example, a domestic cistern in a wetter part of the Roman Empire could be relatively small and still function as it would be regularly topped-up by rainfall, whereas in dryer parts, rainfall is likely to be less frequent, so cisterns need to be larger in order to continue supplying water over the longer gap between rainfall events. Although the amount of water considered necessary will be influenced by the local culture, the need for larger cisterns in areas of infrequent rainfall remains. When rainfall is the source of water for the cistern, the size of the cistern will also be determined by the available catchment area. Many Roman houses had a cistern fed by a compluvium roof (Ellis 2000, p. 26). This can be compared with some of the cisterns in Carthage which collected water from large areas of paving (Wilson 1998, p. 69) and Petra where small dam structures were constructed in the mountainous areas around the settlement and the captured runoff conveyed to large cisterns (Ortloff 2009, p. 249). The Tiddis baths, in modern Algeria, relied on harvested rainwater (Hodge 2002, p. 61). As baths require a substantial amount of water to function, the catchment area used to collect rainwater must have been large and the rainfall regular.

The size of cisterns that rely on rainwater as their only source are determined by the available catchment for collecting water – this will often be limited by the topography (the amount of area upslope of the cistern) or by competition for land use. This is especially true in towns and cities where there is pressure on space, unless arrangements similar to those in Petra can be used where the collection area is located some distance from the cistern. If the water source is not rain water but flow from an aqueduct either spring or river fed, this limitation on cistern size can be removed. Spring flows tend to be more continuous than rainfall, although they may have considerable seasonal variation. When a cistern is linked with an aqueduct, it implies a shortfall between the water the aqueduct can supply and the water the population requires. The time-scale of this shortfall may vary:

- If a spring is abundant during the winter but scarce during the summer, a cistern of sufficient size could be filled with excess flows in wetter months and then be used as the main supply in drier months.
- The time-scale could be a lot shorter, with aqueduct flow collected during the night (when the demand for water is very low) required to meet the higher demands for water during the day.

- It could also be strategic, or a perceived risk of shortfall, in the case of cisterns providing a resource in the event of a siege or significant damage to the aqueduct.

- The shortfall in supply could be created by a high-volume, short duration demand. This is the case with public baths, for example the Bordj Djedid cisterns (20,000 $m^3$) associated with the Antonine Baths in Carthage (Wilson 1998, p. 81) and the 11,500 $m^3$ cisterns at the Baths of Caracalla in Rome (Manderscheid and Garbrecht cited in Wilson 1998). Similarly, in Petra, a system of connected cisterns was able to supply trading caravans that would pass through the settlement (Ortloff 2014, p. 93) and in Misenum, near modern Naples, the 12,500 $m^3$ Piscina Mirabilis may have supplied the naval base and commercial harbour (Hodge 2002, p. 279, De Feo *et al.* 2010).

A cistern fed by an aqueduct can be constructed on a larger scale. In North Africa, Thessaloniki and Constantinople there are examples of cisterns with volumes ranging from several thousand $m^3$ to enormous open air reservoirs of over 200,000 $m^3$. An adequate inflow is not the only requirement for large cisterns: the design and construction techniques used also become increasingly important. A small cistern can be constructed relatively simply. Hellenistic cisterns in Morgantina (modern Sicily) tend to be flask or bottle shaped, carved out of the ground and plastered with lime (Crouch 1993, p. 25-26) and Roman villas commonly included an impluvium and a cistern beneath it (Ellis 2000). In Punic Carthage cisterns had volumes of less than 15 $m^3$ and were narrow, long and deep. These were roofed by slabs spanning the width of the cistern, which constrained how wide the cistern could be. For larger cisterns, there are two main design factors that need to be considered:

- Location — the position of the cistern within the landscape. For example, is the cistern completely underground, dug into a hillside, or entirely above ground?

- Roofing — the majority of cisterns in urban settings were covered, although the very largest in Constantinople were not.

The location of a cistern in the urban environment is dependent on the available space below the water source and the mechanism for extracting water. The topography of the location will also impact the size and design of the cistern. In Constantinople most cisterns are designed to be entirely or largely underground on all sides. For the largest cisterns, such as Aetius, Aspar and Mokios in Constantinople there are relatively few suitable locations. Indeed the long narrow shape of Aetius is probably due to the narrow ridge of flatter ground where it is placed – both Aspar and Mokios are close to square in plan. The completely buried design allows the ground to assist the walls in resisting the force of the water within the cistern although the walls must be able to withstand the force of the ground when the cistern is empty. The underground design makes the inlet arrangement straightforward, allowing water to enter at a high level, however extracting water in large quantities is more difficult – unless water is to be extracted as if the cistern were a well, that is, lifted manually through the roof of the cistern, tunnelling is required. This can be avoided if the cistern is built into the side of the hill, as with the Fildamı and Unkapanı cisterns and, to a lesser extent, the Binbirdirek and Basilica cisterns in Constantinople (see Figure 3.2) or the Dar Saniat cisterns in Carthage (see Wilson 1998, Fig 3).

Figure 3.2: The Unkapanı and Fildamı cisterns. Left – exposed wall of the Unkapanı cistern with buttress style construction, the rear of the cistern is embedded in the hill. Right – the Fildamı cistern with the exposed front wall in the foreground and in the background the buttressed back wall which supports the ground behind.

These cisterns are supported by the ground on one side and exposed on the other, giving easy access to the lower levels of the cistern, but requiring walls that can withstand the water pressure unsupported. Locating a cistern on a hillside also requires less excavation. Occasionally cisterns are constructed entirely above ground, although this makes inlet arrangements more complicated (unless the cistern is collecting rainwater from its own roof). Examples of larger cisterns constructed above ground include Küçükyalı[14] on the Asian side of Istanbul and the Loutron in Salamis on Cyprus (Stewart 2016).

Roofing technology is the key to cisterns' growth in an urban setting as it enables construction on top of the cistern if necessary. Large cisterns are made possible by the development of the barrel vault, which allows a much greater width than a roof of spanning slabs. To construct even larger cisterns, the roof can comprise multiple barrel vaults supported on internal walls that are pierced to allow for movement of water. This type of construction is seen in the large cisterns in Carthage[15] and Uthina[16] both in modern Tunisia. In the Piscina Mirabilis cistern in Misenum, the wall that supports the barrel vault roof is supported on arches spanning between piers, creating a greater volume for water storage.[17] In Constantinople, cross-vault roofing was used, supported by stone columns as seen in the Binbirdirek, Basilica and Şerefiye cisterns (or a combination of stone columns and brick piers as in the Unkapanı cistern). This maximised the capacity of the cistern and, as argued by Stewart (2016), provided a modular structure that improved stability and made design calculations more straightforward.

### 3.2.2 Water Quality

Water quality was an important factor in Roman times: Frontinus declared the water in the Aqua Alsietinia as "positively unwholesome" and in the Anio Novus "muddy and discoloured" whereas the water from the Aqua Marcia was of "excellent quality" (Frontinus Aqueducts of Rome trans. Bennett 1925). Although both Pliny (Plin. Nat. 31.21) and Hodge (2002, p. 60) state that water

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[14] Küçükyalı is an unusual case: the cistern has been constructed above the natural ground level then the ground built up around it to create an artificial hill. See Ricci 2008.

[15] The La Malga, Dar Saniat and Bordj Djedid cisterns. Wilson 1998, figs 7, 3 and 11 respectively.

[16] Wilson 2001, p. 85-86 fig 7.2

[17] De Feo (2010) describes it simply as barrel vaulted (which is technically true). However the arch arrangement is clear when looking at photographs of the site.

from wells was usually more desirable than cistern water for drinking,[18] cisterns did incorporate a number of design features to improve (or maintain) the quality of water that was stored within them.[19] The hydraulic mortar with which cisterns were usually sealed would prevent ingress of ground water as well as preventing leaks. The bottle-shaped cisterns found in many Greek settlements had small openings (usually combined with a wellhead structure) to prevent debris and contamination from entering the cistern. The narrow and deep configuration helped to keep the water temperature cool in hot climates and some excavated cisterns have rounded bottoms designed to collect particles and debris that settle out of the water over time (Crouch 1993, p. 25), showing that practice did tend to correspond to the writings of Vitruvius (see n.19).

Storage of water still forms part of water supply systems today and with modern knowledge and tools we have a clear understanding of what happens to water as it is stored. Before entering the treatment system, 'raw' water is stored in reservoirs where it goes through a number of physical, chemical and biological changes. Over time gravity will cause particles to settle out of the water, reducing the suspended solid content. When water is exposed to sunlight, ultra-violet radiation reduces the micro-organisms and bacteria that can cause disease (Twort, Brandt & Ratnayaka 2000). However, although sunlight removes some micro-organisms it can encourage others, particularly plants and algae which can be harmful to human health. Without the circulation of water, caused naturally by wind or artificially by jets or air bubble systems, the quality of the water can deteriorate. This can include a reduction in the dissolved oxygen caused by plant and bacterial action. Although the Romans and Byzantines did not have our knowledge of bacteria and micro-organisms: they judged the quality of water by both taste and visual observation and therefore had procedures for removing suspended solids (for example the Grotto Sconce settling tank in Rome which settled particles from the Anio Novus, which took

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[18] As it was fresher. There were some exceptions however. For example, in Pompeii, volcanic activity is believed to have tainted the groundwater, causing a change in taste and making other sources preferable (Keenan-Jones 2015, p. 196).

[19] Vitruvius recognises that when the cistern must be used (on account of other options not being available) it is possible for the cistern to be designed to settle sediment out to improve the quality (Vitruvius Book VIII ChVI 14).

water from the River Novus and therefore had a higher suspended solid content than the other aqueducts which drew their water from springs) and writers set out the received wisdom, Pliny stating that running water is preferable to stagnant, sluggish water (Plin. Nat. 31.21). On this basis he condemns cistern water as full of "slime [and] numerous insects of a disgusting nature". Vitruvius is perhaps a little more understanding, accepting that cisterns may be necessary where there are no other options for collecting water and suggests linking together two or three cisterns together, effectively as a series of settling tanks to make the water more wholesome (Vit. VIII ChVI 14-15). Both Pliny's and Vitruvius's comments appear to refer to small domestic type cisterns, collecting rainwater from roofs or other areas and although there was potential for deterioration in quality for stored water, there is evidence that mechanisms for improving water quality were considered when designing and constructing cisterns both small and large. The large geographical range and long period of use of cisterns indicates that cisterns were an important part of providing a reliable and safe water supply.

Most cisterns had a couple of basic design features to keep the quality of water high: they were covered, either with a permanent roof or a removable wooden cover; and many cisterns had small openings that allowed for air circulation but minimised the amount of light reaching the water. The cover prevented debris polluting the water and protected the water from the light, which would have reduced the growth of plants and algae. The air circulation would also have had some benefits, promoting mixing which would help combat a drop in the dissolved oxygen levels.[20] Although perhaps more effective would be the regular inflow and outflow which would keep water moving. Unlike small domestic cisterns, which might be filled during a wet period and then kept as a reserve, only to be used if other sources failed, the larger cisterns connected to aqueducts are likely to have had a fairly regular through flow. Water flowing into large cisterns would slow significantly which would cause some particles to settle out and accumulate at the bottom of the cistern. At the Dar Saniat cisterns in Carthage, there is a sophisticated pre-storage settlement tank system. Incoming flow from the aqueduct is directed into a deep settling tank which overflows,

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[20] Clearly this would not be as effective as wind across the water surface of an open reservoir.

partly into the first pair of cistern chambers and partly into a second set of settling tanks which further improve the water before discharging into the second pair of cistern chambers. All the water is improved to some degree and that entering the second set of chambers is improved the most. The outflow from the cistern chambers is also separated, keeping the highest quality water uncontaminated, with an outlet above floor level providing further opportunity for settlement within the cistern chamber (Wilson 1998, p. 70-71). In Bararus, the inflow to a cistern cascaded down a series of steps which aerated the water (Hallier 1987), which would have improved its taste.[21]

However there are also numerous cases of open-air cisterns across North Africa and the Near East and the majority of Constantinople's storage capacity was within three open reservoirs. The exposure to sunlight (and wind) would have had some quality benefits although these are ones which the Byzantines would not have been aware of. The growth of plants and algae is partly dependent on sunlight and partly on the presence of nutrients in the water. In modern times high levels of nutrients are washed into watercourses from agricultural land, so it is possible that the water in Constantinople, fed by springs and conveyed in a closed channel through Thrace, had relatively low levels of nutrients and so the open air cisterns were not greatly affected by algae. Although the walls of these huge cisterns remain, there is no evidence of how water entered or exited either Mokios or Aetius. At Aspar, there are some indications of how water may have been removed from the cistern. A structure, illustrated in Figure 3.3, close to the northern corner of Aspar, serves as a junction between a channel that runs parallel with the north east face of the cistern and a smaller, perpendicular channel which appears to connect with the Aspar cistern at a low level.[22] If this structure was an offtake, it allowed water to be taken from well below the surface level (assuming the cistern was filled to a reasonable level) and below the top layer of water that would be most likely to be contaminated with algae.

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[21] Wilson found evidence of aeration mechanisms at several cisterns in Tunisia and suggests this as a possible interpretation of some features found in Pompeii's aqueduct as it enters the city (Wilson 2006, p. 503)

[22] There is no evidence of the channel on the internal wall of the cistern, though it may be obscured by a ramp built to allow vehicle access into the cistern. I would estimate the depth of the structure to be less than the known depth of the cistern so if the channel does connect with the cistern it does so above the level of the base of the cistern.

Another open air cistern in Constantinople, the Fildamı which is outside the walls, has a better preserved offtake structure, which also draws water from a lower level, and also aerates the water as it leaves by channelling it into a vertical drop tower (see Crow *et al.* 2008 p. 132-7).

Figure 3.3: Structure to the north of the Aspar cistern. It may have been used to control water flowing from the cistern. Left – photo (K Ward). Right – sketch (F Ruggeri).

### 3.2.3 Were all Roman "cisterns" actually just settling tanks?

In stark contrast to this discussion of cisterns, Moreno Gallo (2016) states that cisterns that have been dated to the Roman period were not for the purpose of storage but instead were actually settling tanks, used to decant mud and pollutants from water (Moreno Gallo 2016, p.122-3). He claims that this frequent misunderstanding is "due to the traditional lack of participation of competent engineers in this domain". Are his claims valid? He makes a number of key assumptions in his argument, firstly that storage was not necessary because "the flow rate provided by the aqueduct (sometimes by many of them) was very high and very consistent throughout the year". Though the *ideal* spring to serve a city certainly would be both consistent and high in its yield, not every city had access to such a spring. Constantinople[23] suffered shortages in the summer but had an abundance of water at other times of year (Procopius, *Buildings* I.xi.10-11) and in Rome there were arrangements in place for supplementing the Aqua Marcia (Front. I.12, 14 II.72) "whenever dry seasons required an additional supply". This contradicts Moreno Gallo's assertion that "the flow rate… was… very consistent throughout the year". Equally, there appears to be great variety in the amount of flow that different aqueducts carried, which contradicts his assertion that it was consistently high. Barcino had access to a high yielding spring (and leaves evidence of only two domestic cisterns) (Orengo and Miró 2013) whereas in Ephesus the flows arriving from the aqueducts were relatively low: the two smaller aqueducts only had capacities of 10 l/s and 20 l/s (Öziş *et al.* 2014, p. 1016). The multiple-solution approaches that are found across North Africa, giving citizens access to water from wells, rain collected in small cisterns and aqueduct flows through large cisterns (Wilson 2001) seem to suggest that the inhabitants had less confidence in their aqueducts than Moreno Gallo does. The need for storage, as discussed above, is not simply a function of the supply, the demand must also be taken into consideration. High volume demands (such as baths) will almost certainly require water to be stored. Therefore it is reasonable to dispute the claim that storage was simply not required.

To consider his claim that all Roman reservoirs are actually settling tanks, Moreno Gallo gives the specific example of the La Malga cisterns in Carthage. These are a large complex of connected parallel barrel-vaulted chambers on the edge of the city. The outlet arrangements of this cistern are not clear – it would appear that several of the westernmost chambers (those furthest from the inlet) have been lost over time (Wilson 1998, p. 74 n.47). One key piece of evidence against La Malga being a settling tank is the retrofitting of a transverse chamber running along the southern side of the parallel chambers. The Zaghouan aqueduct appears to flow into this chamber in the eastern corner of the cisterns and from here into the main structure (see Wilson 1998 Fig. 7). The

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[23] About which Moreno Gallo has some sweeping and rather uncomplimentary views: the construction of Constantinople's cisterns are directly implicated in the Justianic plague and are "the starting signal for the technical-scientific medieval misery at the time when the Roman sanitary engineering died"

transverse chamber would have helped to distribute water between the chambers, creating a bypass of the slow sequential flow that is necessary in a settlement tank to cause the deposition of solids. Added to this, the nearby Dar Saniat cisterns clearly have a series of pre-storage settlement tanks that would not be necessary if the cistern itself was purely a settlement tank. The Romans used cisterns for storage purposes and, where necessary, were able to construct settling chambers on a much smaller scale than Moreno Gallo suggests.

## 3.3 Water supply in other settlements

Every settlement must supply water for its inhabitants; otherwise it will not last very long. As noted by Hall, this "basic task of human existence" is "infinitely harder to manage [for big cities] than small towns or villages" (1998, p. 611). Most communities will be established where the local water resources can support them, but when those communities grow beyond the local capacity or conditions change, significant effort must be invested in securing a new water supply. The solutions used by the community, as with all civil engineering solutions, will be specific to the site and dependent on the topographical context, availability of resources and technology, and expectations of the users. Nevertheless, there are clear common approaches and we can learn about the different types of challenge faced and how they were overcome by looking at how other settlements approached water supply. There are three potential water sources: groundwater, rainwater, and surface water from rivers, lakes or springs. Typically, settlements will initially rely on groundwater, then as they grow move to using surface water. Rainwater collection is common on a domestic scale in many Roman era settlements but it also forms part of the community-level supply in settlements in more arid areas. Groundwater, usually exploited by wells, needs to be lifted to surface level, making it less suitable for some high-volume uses such as public baths. Groundwater levels can also be lowered by overuse, so the work required to lift water increases over time and can become impractical. Using rainwater as a source requires space both for collection and storage, and as such can become less practical when settlements become more densely populated and pressure on space grows. Without electricity to power pumps, lifting water in large quantities was labour intensive, so if the water source was distant, gravity was used to convey water to the settlement, *i.e.* there had to be a downhill route that the water could flow along. When the surface water source being exploited is at some distance from the town, creating the downhill channel can be challenging and costly. Yet in the Roman world this investment was often made as it was the most reliable way to provide a plentiful supply of water that met the demands and expectations of water use.

Once the source has been selected, the method of distribution needs to be considered. Water supply can be largely individual as might be the case with household wells and domestic rainwater harvesting. Although, as the Greeks (Crouch 1993, p. 244-5) were aware, wells positioned too close together can result in rapid drawdown of the water, so it is unsurprising that as populations grew, water supply became a municipal-level task, with water supplied to the people through a combination of private (sometimes paid for) and public supplies. In the Roman period public water supply was typically collected from fountains[24] for free.

Understanding the approaches taken by other settlements provides comparative evidence for what the common issues of water supply are and the different methods for overcoming them. Although each settlement takes an approach suited to its combination of topography, resources and expectations, developing an awareness of these different solutions assists when filling in the gaps of Constantinople's water supply. Here we consider Pompeii, which offers a comprehensive (though not complete) view of distribution within a small city; Ephesus, which uses a largely terracotta rather than lead piping system and reveals how water supply has been used by industry; Carthage shows the sophistication of large cisterns and demonstrates how settlements in more arid areas approached securing water resources; whereas Barcino is the opposite – a settlement with a more than abundant spring nearby; Petra offers another approach to making the most of limited resources in the Near East; Thessaloniki, as the second city of the Byzantine Empire, offers some evidence of administrative control of the water supply; and finally Rome, the only city of

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[24] For one fountain in Cirta, Algeria, an inscription reveals it was provided with six drinking goblets (attached to the fountain on chains) and six hand towels for use by the general public (Wilson 2001, p. 84).

comparable size to Constantinople, from which a detailed account of the administration of the water supply has survived and where many of the structures outside the city have been extensively studied. Other major cities have not been investigated in detail but, as with those considered here, each had to make use of its available resources. Alexandria had a plentiful source of water, diverted from the Nile and stored this water in sizeable cisterns (see Hairy *et al.* 2011) which it would have needed for its large number of water users, including over 1500 baths (Saradi 2006, p. 325). In Antioch, aqueducts, including one constructed by Hadrian, brought water into the city, although there were also springs. The quantity of water available was clearly large as it was able to support numerous baths (including 20 public baths, some open-air baths (Saradi 2006, p. 325)) and was able to provide water for the large army during the Persian war (Libanius Or. 11. 125, 220 and 178 *trans.* Norman 2000).

### 3.3.1 Pompeii

The settlement of Pompeii was located on the Bay of Naples at the foot of the Mount Somma-Vesuvius volcano. At an early point in the settlement's history it relied on public wells and rainwater collected in domestic cisterns but by the Augustan period (27 BC–14 AD) the wells had been decommissioned and replaced by an aqueduct-fed system. The source of the aqueduct is debated, with three possibilities: an aqueduct shared with the upstream settlement of Avella (Lorenz *et al.* 2012); a branch from the regional Aqua Augusta; or a local spring from the slopes of Mount Somma-Vesuvius. Keenan-Jones (2015) argues that one of the latter two options is most likely. A shared aqueduct (the regional Aqua Augusta, or possibly the Avella Aqueduct) is an interesting prospect; there would have been competition for water as the amount of water available in the aqueduct was too low to supply all the connected towns (Keenan-Jones 2010). Using an aqueduct this way would require cooperative management, communication and decision making to balance the conflicting needs from each settlement.

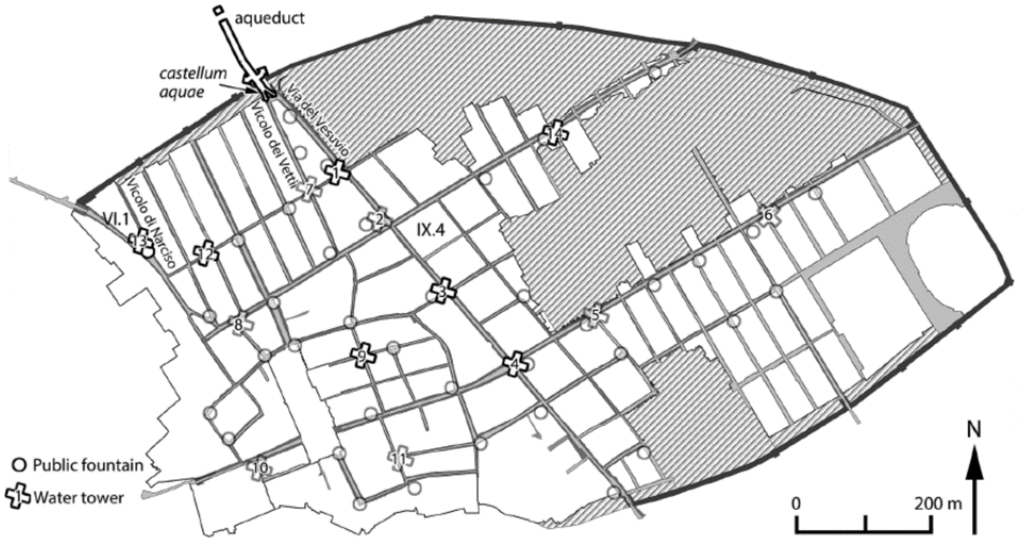

Figure 3.4: Pompeii showing location of water towers, fountains and the point at which the aqueduct enters the city into the castellum aquae. From Keenan-Jones (2015).

The aqueduct entered at the town's highest point and discharged into the castellum aquae that contained a splitting chamber controlled by sluice gates (Hodge 2002, p. 282-3). This chamber provided a means of controlling quantities of water distributed to three conduits which are assumed to have served different areas of the town. Water towers, over 6 m high, were located throughout the town to distribute water to public fountains and private users (see Figure 3.4 and Larsen 1982). The towers had a lead-lined basin at the top which fed the local area through lead pipes running from the base of the basin creating a local low-pressure network where water is driven through the pipes by the head of the water in the tower (Wilson 2008, p. 303). This arrangement created a consistent water pressure across the settlement and prevented pipes having to resist the full pressure of water caused by the drop in elevation across the town – near the boundary at the southern edge this would have been equivalent to a 30 m high tower. Larsen (1982) maps 11 of the brick towers in detail and discusses the positioning within the town which appears to be related to both the drop in elevation and the number of water-users requiring an offtake from the tower. This results in an uneven distribution of towers which can be contrasted with the even distribution of fountains which resulted in most of the population living within 50 m of a public fountain from which they could have collected daily water supplies (Eschebach 1983, p. 104). Consumers of large amounts of water – such as laundries and other textile industries – would have had a private connection from a water tower. About 10% of houses also had private water connections, which were primarily used to power fountains rather than provide drinking water (Wilson 2008, p. 304).

### 3.3.2 Ephesus

Ephesus, one of the largest settlements in Roman Asia Minor[25], was appointed the administrative centre of the eastern provinces by the Emperor Augustus. Located in modern western Turkey, the city originally had a harbour but it is now a considerable distance from the sea because of siltation by the two local rivers. The key elements of water system found in Ephesus are the terracotta piping feeding the city's fountains and the water-powered mills that reveal how water supply can serve industrial purposes. In the Roman period, water was brought to Ephesus through four aqueducts, tapping spring sources to the south, east and northeast (Ortloff 2009, p. 296, 320). The estimated capacity of two of the four aqueducts is very low: 10 l/s, 20 l/s, 100 l/s and 200 l/s[26] (Öziş *et al.* 2014, p. 1016).

Each aqueduct served a different area of the city, although only one appears to use a castellum aquae as the starting point of distribution. The other aqueducts have branches cut directly from the aqueduct line. There is no clear evidence of how flow into these branches was controlled, although it would appear to be necessary to have a mechanism to prevent all the water being used in the first branches and leaving downstream branches with no supply. As the majority of the settlement was located on the lower slopes of two hills – Panayır Dağ and Bulbul Dağ, and the aqueducts enter the city from high elevation, the settlement was able to use the fall of elevation across the site to convey water to the users within the city. Several fountains in Ephesus are designed to prevent

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[25] Population estimated by Wilson (2011, p. 187) as 33,600 in the Roman period (2nd century AD) based on a population density of 150/ha.

[26] These are basic calculations and do not take into consideration changes in slope which would have created bottlenecks in the system and have reduced the actual maximum capacity. And it should be noted that capacity does not necessarily equal flow, but only provides the maximum boundary of possible flow.

excessive waste of water, with fountains often fed from the basin of another fountain further upslope (Ortloff and Crouch 2001, p. 845). Water was distributed through the city by a network of pipelines (Pickett 2016 recorded 350 pipe sections found across the city) that as well as feeding temples and public fountains also supplied private households (Ortloff and Crouch 2001, p. 854). In late antiquity, the water in Ephesus was used by industry to power a number of mills. In the 6th and 7th centuries some of the older buildings in Ephesus were converted into workshops; within these workshops there is evidence of at least 8 waterwheels that used the 25 m drop over the site to power flour mills and a stone sawing machine (Wefers & Mangartz 2010).

### 3.3.3 Carthage

Located on a headland by the sea and backed by the low lying plain of Ariana, Carthage initially had to rely on limited local water resources. As the population grew and the available technology improved, Carthage implemented various strategies to obtain the required water resources. The arid climate and unpredictable rainfall was a challenge that required a quite different approach to water strategy than that seen in Rome.

In the Punic period (before it became part of the Roman Empire), the population initially relied on a natural spring and local wells which were then replaced by moderate sized domestic cisterns (<15 $m^3$) designed to catch rainwater. These cisterns, narrow but very deep[27] were recovered and rehabilitated after Carthage was razed and rebuilt as part of the Roman Empire. During the Roman period new cisterns were added, using new barrel vaulting techniques to construct larger storage spaces that served as public cisterns collecting runoff channelled from public spaces such as courtyards. Wilson (1998, p. 69) explains that this points to management of water for different purposes as water collected from public spaces is unlikely to be considered suitable for drinking purposes. Some of the cisterns here, as at other North African sites (Wilson 2001, p. 84) are very large – the Bordj Djedid cisterns, associated with the Antonine Baths are 20,000 $m^3$ and the La Malga cisterns are estimated to be at

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[27] Wilson (1998) reports that the width of the cisterns was limited by the roofing approach – either a slab laid flat across the cistern or two slabs pitched against one another.

least 50,000 m$^3$ along with other cisterns of a few thousand m$^3$ (Wilson 1998, p. 76), the largest known before Constantinople. The remains that are recorded show sophisticated inlet arrangements with settlement tanks and storage segregated by water quality and outlet arrangements with multiple pipelines and taps to control the direction and quantity of flow (See Wilson 1998; Fig 3 of the Dar Saniat cisterns and Cagnat and Chapot 1916 for the original).

Eventually the water available locally was insufficient to supply the town and the 90 km Zaghouan aqueduct was constructed in the 2nd century, crossing the low-lying plain of Ariana on a 20-m-high arcade which brought water to the city at an elevation sufficient to reach many parts of it. The aqueduct fed the public baths (via the Bordj Djedid cisterns) and supplied an urban distribution network. The large cisterns in Carthage are at the outskirts of the city and do not appear to form an integral part of the urban network. Vernaz (1887) records connections into a branch of the aqueduct line within the city and the remains of a control feature within the aqueduct, probably some manner of sluice gate, which indicate distribution directly from the aqueduct line rather than from a castellum structure. Overall, the studies of Carthage, like many where exploration of the remains are constrained by modern settlements, cannot offer a comprehensive picture of the settlement's water supply. However, the details that are available reveal an elaborate and sophisticated approach to water quality and a willingness to adapt techniques to suit the local geography and as conditions changed.

### 3.3.4 Barcino

Barcino was the Roman settlement at modern Barcelona on the east coast of Spain. In Barcino we are offered a view of what a Roman city does when it has more water than it needs (Orengo & Miró, 2013). The water source chosen for the settlement was the Montcada spring, which was both of good quality and high yielding.[28] The aqueduct approached the settlement on an arcade to ensure

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[28] According to Orengo & Miró (2013) the yield of the spring in the late 19th century was measured at about 38,800 m$^3$/day (=449 l/s) and there was little evidence of sinter build up (a calcareous deposit, sometimes called travertine, that can precipitate out of water from springs) in channels or pipelines. This can be compared with the Collserola spring that was used to feed a later medieval pressurised

sufficient height to serve all areas of the city. Orengo & Miró (2013) argue that there is a single aqueduct that splits into two channels outside the settlement wall (see Orengo & Miró Fig 2a and Fig 4) in order to serve separate areas of the city. No evidence of castella has been found but their presence can be inferred, as discussed in Orengo & Miró (2013, p. 257). From these castella, water was distributed differently depending on final use – the private water supply was a pressurised lead-pipe system whereas channels delivered water for industrial and recreational use. The pressurised system would allow private users to operate fountains – and this was possibly the main function of the piped system as many excavated houses also had wells as another water source. The channels delivering water to industry and baths were more practical for delivering large quantities of water. There were abundant bathing facilities – each *domus* excavated so far has its own bathing complex and there were a number of public baths available for ordinary citizens. The abundant water available also led to the development of a drainage system capable of dealing with the constant overflow of unused water. The arrival of a flowing water source (such as an aqueduct) in a city was often associated with considerable development in drainage facilities (see Keenan-Jones 2015, p. 118-119 for similar observations in Pompeii).

### 3.3.5 Petra

Petra, in the desert mountains of Jordan, was an important trading city established by the Nabateans in about 300 BC that became part of the Roman then Byzantine Empires. Water in this area was precarious and unreliable yet Petra managed to support a thriving trading city for centuries. Ortloff (2009, 2014) provides a comprehensive description of the city's water supply elements. To address the water scarcity of the region, Petra adopted a water supply system that made use of multiple sources, augmenting a perennial spring with dams and storage structures that diverted and collected rainwater when it was available. Flooding was an issue too – the settlement was located at the meeting point of a number of wadi canyons that supported ephemeral surface flows in

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system but had a much lower yield (only 300 m$^3$/day) and caused maintenance issues with sinter build up in pipes.

storm conditions. The bare rock of the canyons could rapidly collect and channel flood flows during storms, so the many small dam structures around the settlement not only collected water but protected the main settlement.

Petra's main water supply relied on flow from a local spring that was originally delivered through a low level open channel but was later reworked to flow into the city at a higher level through a pipeline carried in a channel in the rock (Ortloff 2009, p. 253). This primary water source was supplemented by the Zurraba reservoir which was fed by both rainfall runoff and excess spring flow and was the source for one of the aqueduct pipelines into the city as well as providing additional flow to the main spring pipeline in the dry season. In addition to these two main sources, rainfall runoff water was collected all over the city in cisterns – Ortloff (2009, p. 258 and Fig 2.1.3) reports that so far over 200 have been discovered. In the city, piped supplies provided water to some private houses and the public nymphaeum, with the many smaller cisterns providing locally available water at times when the piped spring flow was not available. The multi-source approach adopted by Petra allowed it to have sufficient water security in an arid region to support industry (Ortloff 2009) and the large trading caravans that travelled through the region.

### 3.3.6 Thessaloniki

Thessaloniki, the second city of the Byzantine Empire, had a population of approximately 40,000 and a water supply system fed by three main aqueducts. Gala Georgila (2015) has investigated the city's Ancient water supply, mapping the aqueducts outside the city and drawing together the available information on the cisterns, channels, pipes and sewers found within the city.[29] The Byzantine era city was located on a slope between the foothills of Mount Chortiatis and the sea. The slope is divided by natural drainage into a series of parallel ridges and valleys like a corrugated roof and these divisions effectively constrain the water supply system which, entering the city at high points

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[29] Gala-Georgila kindly provided the UoE team with an English summary of her thesis and presented her work at two workshops we held in Edinburgh and Thessaloniki.

through three aqueducts, splits into a series of five parallel systems (see Figure 3.5). 84 cisterns provided storage within the city, with the largest at 5000 m$^3$.

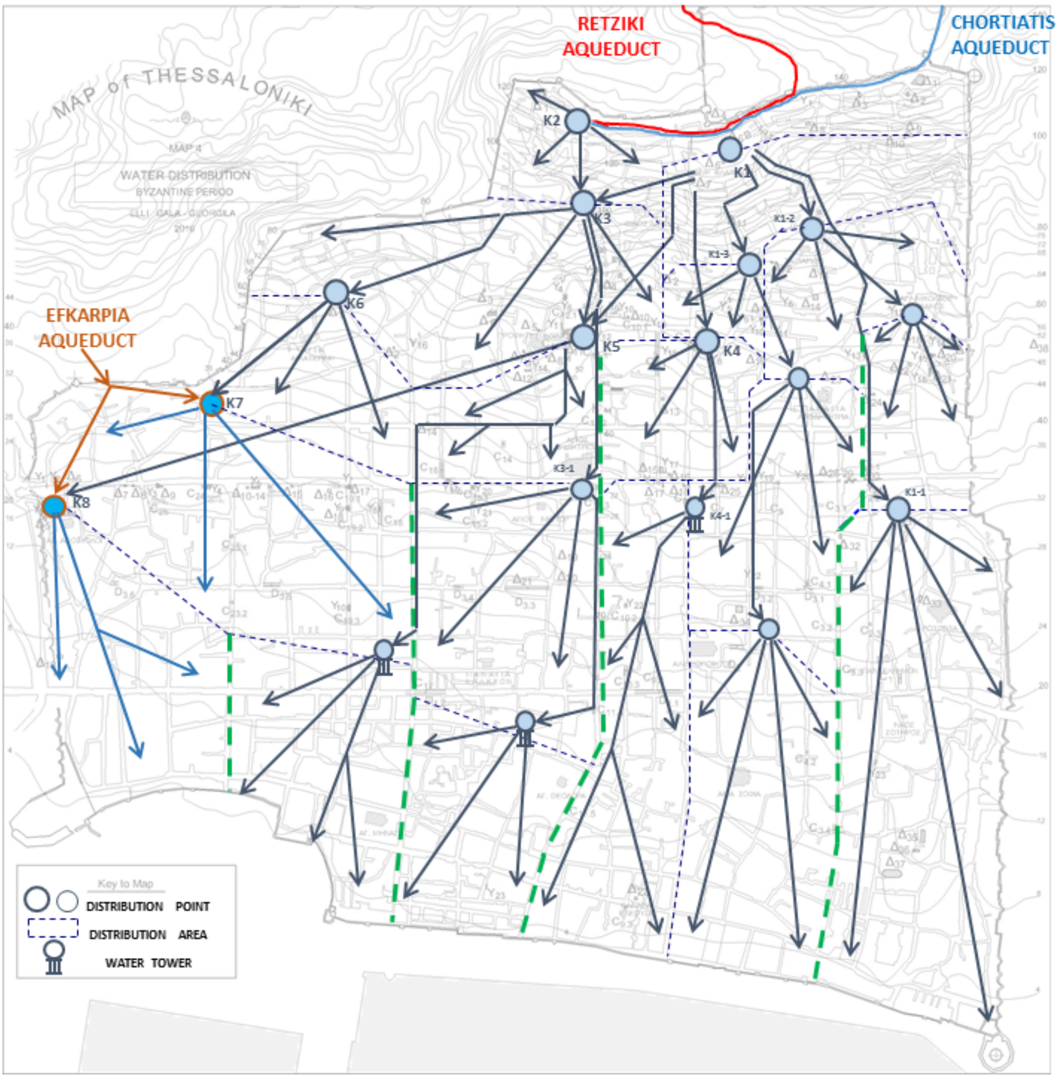

Figure 3.5: Water distribution in Thessaloniki is split into sectors by the topography of the city (Gala-Georgila pers. comm.).

The entire system appears to have been closely linked with monasteries which were often located at the head of the parallel systems. From their positioning on top of the water supply systems as they flowed down into the city, it is assumed that the monasteries played a key role in controlling the flow of water.

### 3.3.7 Rome

Rome is the most obvious city to compare with Constantinople. Both settlements were far larger than anywhere else in the Roman world (although

Constantinople is estimated at half the population of Rome) and both served as capitals of the Roman Empire. However, as with Constantinople, both its size and the living city on top has made it difficult to study the water supply comprehensively. The 11 aqueducts that fed the city have been well documented, but we are less certain of what the arrangements were for distributing the water supply within the city as very little of the physical infrastructure remains. What we do have for Rome is the contemporary account by Frontinus, *De aquis urbis Romae (On the Aqueducts of Rome)*, which provides detail on the water supply from his perspective as *curator aquarum* (Water Commissioner) of Rome.

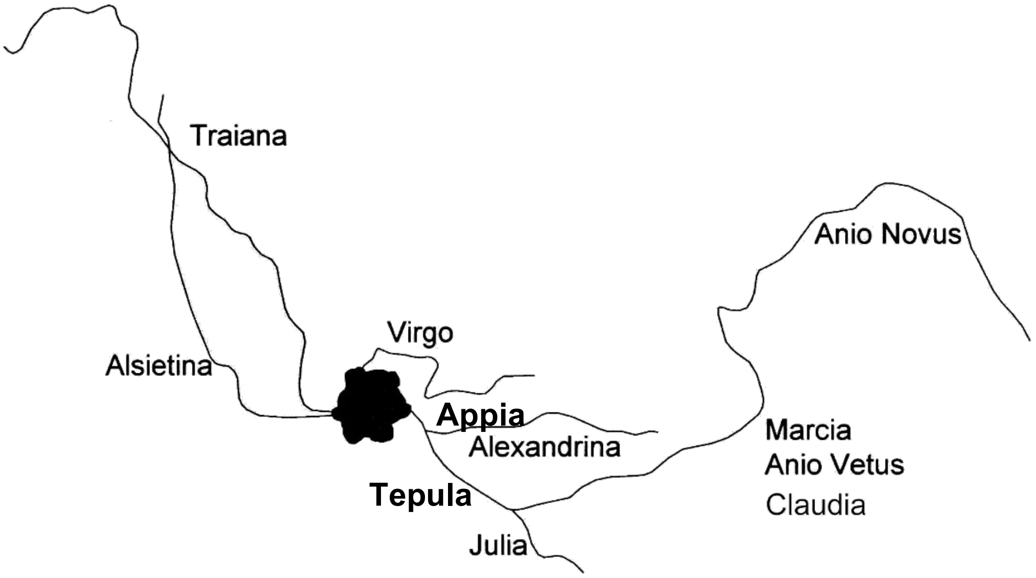

Figure 3.6: The eleven aqueducts of Rome. Many of them followed similar routes and were located on top of each other (image: Snyder).

Rome's 11 aqueducts (see Figure 3.6) were constructed between 312 BC (The Aqua Appia) and 235 AD (The Aqua Alexandriana), and nine of them were constructed and operational when Frontinus was the Water Commissioner at the end of the 1st century. The majority of the aqueducts conveyed water from springs, although the Aqua Alsientina took its water from a lake (and was noted for its poor quality) while the Anio Novus drew part of its water from the Aniene river.

The 11 aqueducts were capable of delivering a huge volume of water – estimates vary from 520,000 m$^3$/day[30] to over 1,000,000 m$^3$/day.[31] Blackman's (1978) more detailed calculations estimate a maximum capacity of 600,000 m$^3$/day from the four largest aqueducts (Aqua Marcia, Aqua Claudia, Anio Vetus and Anio Novus). When the aqueducts reached the city they discharged into terminal castella and were then distributed to 247 secondary castella within the city (Front. 78 trans. ). From these points water was distributed to private houses, fountains, basins and other public uses. There were a huge number of water-related structures within the city, including 1352 public fountains, 856 public baths and 11 thermae (Dodge 2000, p. 171). From Frontinus, we can get a sense of the complexity of the water network – if an aqueduct needed to be closed for maintenance, there was provision to divert its flow into another of the aqueducts; fountains had jets supplied by different aqueducts, providing redundancy to ensure flow in the event of failure of one of the aqueducts (Front. 87); and a group of at least 700 slaves were used to maintain and operate the water supply system (Front. 116-7). Frontinus writes from the perspective of an administrator, with little direct information on the engineering of the system but with the details of built-in redundancy and maintenance procedures we can see that the water supply was understood as a system, with each part interacting to continue serving the citizens of Rome with water. It is reasonable to infer that a similar level of understanding and sophistication operated in the New Rome, Constantinople.

## 3.4 The engineering conversation

Some engineers have become involved in and written about archaeology relating to water supply. They have brought their own perspective, their own questions, approaches and tools to the task of understanding and interpreting the available data. In this section I will review the work of some of the engineers who consider water supply systems located around the Mediterranean and Near East and belonging to the Roman and Byzantine periods and, occasionally, earlier eras.

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[30] Bruun (2012) although it is not clear where this figure comes from – it is based on converting the Roman *quinaria* quoted by Frontinus into a flow rate.

[31] Dodge (2000) cites Grimal (1961), Pace (1983), Forbes (1964) and Aicher (1995) as all estimating daily flows over 1,000,000 m$^3$. All the figures given are slightly different.

Some have written extensively on water supply in other areas of the world, for example Ortloff has investigated a number of pre-Columbian canal systems, but these are outwith the scope of this review.

When an engineer does cross disciplines into archaeology it is natural for them to focus on what interests them, namely, the infrastructure and engineering within the ancient setting. Broadly speaking, there seem to be two approaches for engineers writing about water supply in an archaeological context: descriptive and analytical. Those taking an analytical approach make use of modern engineering techniques: a review of the engineers working in this area is the main focus of this section. When considering the analytical approach, a further split becomes apparent: some take a solely hydraulic perspective, using it to determine the questions asked, methods used and results presented, whilst others combine the hydraulic investigation with more practical considerations. The conclusions of those who take the combined approach, or at the very least express caution about their hydraulic perspective, appear more credible. It is important to differentiate between what we can do and what we can usefully do for our intended audience. As modern engineers we work within a frame of reference that places analysis and optimisation at the centre of the design process. We should be wary of transposing this viewpoint onto the engineers of the past. There is a danger of making misleading inferences about the level of Roman knowledge by using analytic tools on their systems that were not available to them. When an effort is made to detach from the modern frame of reference, the questions used to guide the research and the conclusions made tend to be more valuable and accessible to the archaeological community.

The more straightforward, descriptive approach collects instances and examples of engineering infrastructure and presents the information that is available about them. Examples of this approach include Mays (2014), Mays, Antoniou & Angelakis (2013) on cisterns, Angelakis (2016), Angelakis & Spyridakis (2010) on various elements of water supply within Hellenistic and pre-Hellenistic cultures, Mays, Koutsoyiannis & Angelakis (2007), De Feo, Laureano, Drusiani & Angelakis (2010) on more general development of water management and Schram (2014) on dynamic control structures in aqueducts. These articles serve a purpose identifying and describing infrastructure elements, which sometimes are of only passing interest to archaeologists, often bringing together multiple examples of an element which might be considered only within its particular context elsewhere. By doing this, patterns of development can be seen (as discussed in the section on cisterns) and common approaches identified. However considering infrastructure elements outside of their context removes awareness of the factors that led to a particular choice or use of a technology and thus limits our understanding. Each element is dependent on the system it forms a part of. Overwhelmingly, these studies are descriptive but rarely more than that. There is little in the way of explanation or proposals about how or why the elements studied were used and the wider impact of this choice. The studies report the evidence that there were water supply systems, but do nothing to consider how the wider systems or how they functioned. So these studies can act as a foundation for further work, raising awareness of the available evidence but not moving the arguments of ancient hydraulics forward.

The analytic approach offers more insight. This group of papers use the tools of modern engineering to analyse parts of the ancient water supply systems. Chanson (2000, 2002) uses hydraulic analysis and physical models to understand how Roman drop shafts and other energy dissipation devices would have operated. Blackman (1978) combines interpretation of detailed surveys with hydraulic analysis to calculate the maximum flow in Rome's four largest aqueducts. Haut and Viviers (2007) use computational fluid dynamics (CFD) and other hydraulic analyses to investigate the flow through parts of the water supply in Apamea. Ortloff (2001, 2009, 2014), a CFD specialist, has investigated a range of water systems across the Near East. Smith (2007) considers the pressure pipelines found in siphons and distribution networks from both a technical and practical engineering viewpoint and also makes an argument about the importance of not overstating (or perhaps over-assuming) what a modern engineering approach can reveal about its ancient counterpart.

### 3.4.1 Chanson – physical models and hydraulic analysis

Chanson's investigations of how Roman engineers approached steep sections of aqueduct illustrates how a technical engineering perspective can uncover useful information for the wider archaeological community. He uses hydraulic analysis and physical scale models to investigate the drop shafts which are found on aqueducts across Europe and North Africa. Classifying the potential flow regimes associated with the structure geometry and flow rate is a key tool when trying to estimate the maximum flow through an aqueduct, a result that is of interest not only to engineers but also to archaeologists and historians. At higher flows, water falling through the dropshaft causes so much erosion to the downstream channel that it would rapidly disintegrate (Chanson 2000, p. 59). As many aqueducts were functional for decades and sometimes centuries, we know that the Romans would have avoided this situation – presumably by adapting aqueducts that suffered this problem and eventually adopting a rule of thumb that would prevent its occurrence. This allows the maximum flow that would avoid this scenario to be estimated. Using this approach, Chanson reduces the estimated flow through the Cherchell aqueduct from 40,000 $m^3$/day to no more than 6,600 $m^3$/day (Chanson 2000, p. 61).

He also investigates the detrimental impacts of flow returning to sub-critical after a steep chute and proposes that structures found downstream of steep sections of aqueducts are stilling basins to dampen wave propagation rather than settling tanks for the removal of suspended solids. Some of the most interesting aspects – that the designs used for steep chutes vary widely and some of the designs actually prevented the energy dissipation they should have been performing, may point to a lack of dissemination of knowledge and experience on how to deal with steep slopes and suggest that each structure was a one-off response to the circumstances that the constructors faced. Chanson does not draw this conclusion however, instead he infers a more unified body of Roman engineering experience but does not conclude whether this can be attributed to an understanding of hydraulic principles or just to observations and trial and error. Chanson has written about his work on Roman dropshafts for two distinct audiences: what has been described above is detailed in an article that appeared in the American Journal of Archaeology and he has published different aspects of the work in the Journal of Hydraulic Research (Chanson 2002). Here the focus has been on comparing the performance of the ancient design with modern drop shafts. The conclusion that the Roman design was more efficient at dissipating energy and entraining air is potentially of interest to modern designers but not to non-engineers. In these articles, Chanson draws out different points dependent on the audience. When talking to an archaeological audience he still uses the tools of an engineer but the results and conclusions are of relevance to archaeologists and historians. When the audience are hydraulic engineers, he focuses his work on comparing modern and ancient design. Although this is an interesting aspect for modern engineers to consider, we must do so with caution and not read too much into the finding that ancient dropshafts are more efficient dissipaters of energy. It does not signal that this dropshaft was the result of conscious hydraulic design.

### 3.4.2 Blackman – hydraulic analysis

Blackman (1978) demonstrates what an engineer can do with detailed survey information collected for archaeological purposes. Hydraulic calculations of aqueduct capacity are frequently made but these rarely take into account the full complexity of the aqueduct system which is likely to have changes in slope and channel cross section which will all affect the flow rate. These variations along the length of the channel can interact and further alter the flow conditions. Using the detailed archaeological surveys of the *Anio Vetus, Aqua Marcia, Aqua Claudia* and *Anio Novus* carried out in the early 20th century (Reina, Corbellini & Ducci (1917) for Ashby 1935), he calculates a likely total discharge for the four aqueducts of about 7 $m^3$/s. The width of the channel along each aqueduct varies considerably and Blackman is able to compare his calculated water depths with the channel width (Blackman 1978, p. 71). There is no evidence that the two are related which allows him to conclude that because there was no attempt to optimise channel size for depth it is unlikely that there was a reliable method of predicting water depth or flow behaviour. This is an important point that in contrast with the views of some engineers (see section 3.4.4 below on Ortloff) accepts that the engineers of the time could be enormously successful in achieving their desired goal (delivering water to Rome) without our knowledge of fluid mechanics and without meeting our notion of an engineered design.

### 3.4.3 Haut & Viviers – hydraulic analysis and computational fluid dynamics

Haut & Viviers (2007) use hydraulic analysis and CFD (computational fluid dynamics) to investigate the operation of a section of the water system in Apamea, Syria, focusing on two branches that flow from the main aqueduct, through "room of visit"[32] structures and one into a cistern, the other to an unknown location. The engineering analysis focuses on calculating the energy losses of the various elements of these two sub-systems. The calculations are technical but can be simplified to the conclusions that the first branch is better 'designed' than the second as the energy loss is considerably lower; and that both of the sub-systems are less efficient than a notional modern design. The validity of this approach needs to be questioned. Underlying the approach and conclusions made are assumptions that measuring the energy loss and efficiency is an appropriate way of judging the fitness for purpose of the structures and that there was an awareness and desire to optimise the design in terms of minimising energy loss (and therefore increasing the flow).

This is the difficulty of looking at what we are able to do with our modern tools without engaging an imaginative consideration of the ancient world. Without detaching from our own frame of reference, our context of design and expectations of satisfactory performance can automatically shape the questions asked and approaches taken. We can use the archaeological remains to assess the characteristics of the system, estimating how much water flowed through various sections, but using this to suggest more can be contentious. Consideration needs to be given to what are the worthwhile, relevant and answerable questions for engineers to ask in order to benefit archaeologists and historians.

### 3.4.4 Ortloff – hydraulic analysis and computational fluid dynamics

In addition to journal articles on Ephesus (2001) and Petra (2005, 2014), Ortloff has also published the book *Water Engineering in the Ancient World* (2009) which as well as Ephesus and Petra, examines elements of the water supply in

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[32] I assume this term refers to an inspection chamber.

Aspendos (Turkey), Priene (Turkey) and Caesarea Maratima (Israel). At these three sites, the analysis is confined to a single element of the water supply system. In Aspendos, Ortloff's focus is the behaviour of the siphon as it starts to operate *i.e.* move from a not flowing to a flowing state. By analysing numerical and CFD models he concludes that several points made by Vitruvius on the operation of inverted siphons are correct and suggests that this knowledge had been gained over many years of constructing, optimising and repairing (Ortloff 2009, p. 295). In Priene, the design of an unusually shaped drain outflow is investigated and it is concluded that the shape purposefully creates a complex vortex that would prevent debris settling, clogging the channel and causing flooding where the flow exits through the town wall. Caesarea Maritima is considered in more depth below, along with Ephesus and Petra.

This review focuses on the appropriateness of the questions asked and assumptions made in attempting to understand the characteristics of the water supply in each place. One major issue is the clarity of communication throughout Ortloff's work – with lots of dense technical detail the supporting text is sometimes lacking a clear explanation of the purpose of calculations and implications of the results. At times the consideration of notional and actual situations is blurred so that it is unclear when calculations are based on evidence found on site. These aspects can make Ortloff's writing impenetrable, especially to those without a technical background. As discussed above, with regards to the work of both Chanson and Haut & Viviers, it is crucial to consider the potential audience, particularly when they are not of the same specialism. When the engineer considers an archaeological problem it is incumbent on her to make sure the results are useful and understandable to the archaeologist (or a wider, non-technical audience).

Ephesus and Petra are considered comprehensively, with descriptions of the water supply system as a whole interspersed with detailed investigations of certain elements. As well as presenting these instances of water supply, Ortloff's aim is to build evidence that the engineers of the time had a high degree of hydraulic knowledge and used this in the design process of the systems. He is prone to credit everything as a hydraulic-based design decision, giving little consideration to the practical aspects which, it could be argued, are often the main factor in design decisions. For example, in discussing possible distribution systems, he states that a *castellum* system where individual offtakes are taken from header tanks is preferred because the alternative – a large trunk main with smaller side branches, all under pressure, can lead to unsteady flow delivery rates (2009, p. 306). Whilst it may be true that trunk and branch system could result in unsteady flow, consideration of an example of the castellum system – the distribution system in Pompeii – highlights the positive practicalities that can be associated with this system. In Pompeii, as discussed in section 3.3.1, water was directed from the main castellum at the highest point in the town to a series of 6 m high towers topped with water tanks. From the tanks multiple downpipes led to private house connections, fountains or, potentially, to another water tower.[33] In Pompeii there is a considerable drop in elevation across the site and the towers created a fairly uniform pressure for the distribution network by acting as break pressure tanks (which a trunk and branch model could not do). New connections to the water supply had to be taken from the tank which has administrative advantages by making the connections visible – from Frontinus (Front. II. 103-106) and the review of the law codes in Section 2.4.1 we know that corruption and illegal connections did occur. There were also practical construction advantages – unlike modern water systems where connection to every dwelling is expected, connections to the water supply were rare [34] and not pre-planned and making a new connection into a tank could be more easily managed than into a pressurised trunk main. It would also be easier to isolate sections for maintenance and easier to spot and repair faults on the portion of the system that was above ground. Altogether, there were a number of reasons not associated with hydraulic performance that made the tower system preferable in its own right rather than as a considered and hydraulically superior alternative to trunk and branch pipes. Similarly, as discussed in detail below, the consideration of the gates arrangements in

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[33] Currently there is not enough evidence to understand whether the towers were supplied in this way, from tower to tower or from a series of pipelines from the main castellum. The positioning of four of the towers in a straight line down the slope of the main street (Larsen 1982, fig. 2 p. 43) suggests that they could well have been connected in a chain. Smith (2007) discusses the two options but the precise method of filling the header tanks is not critical for this discussion.

[34] As discussed in section 3.3.1, it is estimated that 10% of houses were connected to the water supply (Wilson 2008).

Caesarea Maritima and pipe design options in Petra do not give enough weight to practical factors.

For Ephesus, the examination of flow rates in pipes under different conditions of length, slope and head illustrates the complexity of the situation faced by Roman engineers (Ortloff 2009, Fig. 2.3.4 p. 303). For shorter pipeline lengths (up to 500 m but generally less than 200 m) the head available can significantly alter the flow rate, but as pipelines lengthen the flow rate is determined by the slope, with head making little difference. In certain circumstances, pipelines will flow only partially full which can be advantageous, delivering more flow under the same conditions as full-pipe flow, however, flow switching between full and partial flow can lead to  fluctuating flow rates and 'glugging' in pipes. Working out where these transitions are likely to occur can be difficult and relies on CFD modelling. How the Romans dealt with such situations is unclear: perhaps the problematic transitions did occur relatively frequently and were accepted as part of the system[35] although they would cause what we would term 'poor performance'; perhaps they had established heuristics that reduced the likelihood of these transitions and potentially the top holes found on some pipes could be used to reduce the severity of the transitions. It is not clear that Ortloff's argument – that top holes were not only used to prevent formation of vacuums during transitions but also as a means of observing the flow regime within a pipe to facilitate altering its slope to remove the unwanted transition (2009, p. 308) – is valid or supported by the evidence. The practicality of moving a pipeline that has been mortared and has water flowing within it has not been taken into consideration.

Another section on Ephesus illustrates one of the communication difficulties raised earlier: the text is often confusing, hard to follow and possibly contradictory. For example, in his description of the Ephesus Fountain House (a castellum) Ortloff, in the same paragraph describes the aqueduct inflow into the

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[35] Pickett (2016) finds evidence that pipes were regularly replaced in Ephesus, particularly ones with significant sinter encrustation. As sinter tends to accumulate at points of turbulent flow, a hydraulic jump could be associated with the pipes found by Pickett.

castellum as 0.258 $m^3/s$ (0.018 $m^3/s$ from the Kenchiros and 3 x 0.08 $m^3/s$ for each pipeline of the Marnas aqueduct) and the outflow as 0.338 $m^3/s$ comprising:

- 0.038 $m^3/s$ from the main castellum compartment into the front basin through the ten holes in the wall (the basin to the rear of the castellum is mentioned but not included in the calculations)
- ~0.3 $m^3/s$ from five (of the eight noted in the text) pipelines emerging from the castellum.

More water is leaving the castellum than entering it; there is a deficit of 0.08 $m^3/s$ (80 l/s), which does not appear to establish the input-output water balance as Ortloff suggests (2009, p. 319; 2001 p. 852). Further uncertainty is created by the latest flow estimates for the Kenchiros (0.2 $m^3/s$) and Marnas (0.036 $m^3/s$) aqueducts (Öziş *et al.* 2014) which are significantly different to those Ortloff used.

At Petra, the 3.5 km Wadi Math pipeline is considered. It was carried in an elevated channel cut into the rock face of the Jebel al Khubtha mountain and delivered water from the Zurraba reservoir to a reservoir near the Sextus Florentinius Tomb and several Royal tombs that would have required water for "celebratory functions" (Ortloff 2014, p. 93). Ortloff compares the pipeline that was constructed, which has a slope of about 2 degrees with two other "design options": a slope of 1 degree and a slope of 4 degrees. CFD models of the two alternatives highlight inferior hydraulic performance – the full pipe flow present in the one degree slope design would create high hydrostatic pressure which could potentially cause leakages and the four degree slope design would create an oscillatory hydraulic jump that would again lead to hydrostatic pressure and potential leakage. Flow in the two degree slope is able to maintain near critical flow along its entire length, therefore eliminating leakage caused by hydrostatic pressures.

This is presented as evidence that the Nabatean engineers who designed and constructed the pipeline had knowledge of the potential leakage problems of the other designs and dismissed them, instead selecting the one that was just right. However, an examination of the design options considered shows that the comparison is contrived. Over the length of a 3.5 km pipeline, the differences in slope have a significant impact on the elevation of the end point of the pipeline: the one degree slope would terminate 60 metres higher and the four degree slope 120 metres lower than the two degree slope. Ortloff does describe the practical implications of these choices – the one degree slope would involve constructing a reservoir high up the mountain slope and the four degree slope would bring water in at a much lower level that might be suitable for the workshop area (2014, p. 94). In essence, these are not comparable 'design options' (the water in the four degree scenario is being delivered to a different, lower area). There are clear practical reasons why the one and four degree slopes are not suitable – they do not fulfil the basic function of getting the water to where it is needed. Yet Ortloff still favours a hydraulic explanation as the prime driver for the decision.

Ortloff's investigation of a control structure in Caesarea Maritima (2009, p. 350-357) is based on two parallel lifting slots in the 12-m wide channel that connects to a large reservoir. A number of arrangements of parallel sluice gates with smaller inset openings are suggested that could reduce the required lifting force, although the conclusion is weakened by the admission that the technology of the period would have been capable of lifting the sluice gate without recourse to the suggested arrangements. And again Ortloff does not consider the possibility of a practical purpose (rather than hydraulic); one which is still commonplace in modern open channel irrigation systems, where a control gate will often have a pair of slots immediately downstream for stoplogs. These allow flow to be controlled if the gate has to be removed for maintenance – the slots seen at Caesarea Maritima could be for a similar purpose.

### 3.4.5 Smith – hydraulic analysis and retrospective analysis

Smith's *The Hydraulics of Ancient Pipes and Pipelines* (2007) provides a comprehensive review of inverted siphons. Combining a modern knowledge of hydraulics and practical engineering with the literary and archaeological evidence, Smith examines what we know of this Roman technique for crossing wide valleys deemed unsuitable for bridge construction. His approach is inherently practical, taking into consideration not just the presence of potential issues but also their magnitude (e.g. accepting that having a turn in a pipeline will produce a force that will need to be resisted but also pointing out that this force is relatively small and quite within the capability of Roman buttresses). When trying to untangle the purpose of pipe holes, high points and tank towers in inverted siphons; three stages of use are considered – start up, normal operation and stoppages for maintenance. He also factors in the need for and impact of on-site construction. This is altogether a nuanced approach that clearly brings in a practical perspective which mirrors the practical approach that Roman engineers are likely to have used to design and construct the inverted siphon structures.

The paper could more accurately be titled *The Hydraulics of Ancient Inverted Siphons* as he dismisses the category of pipes carrying open channel flow in a single paragraph. This can be contrasted with Ortloff's (2001 & 2009) detailed study of the pipes in Ephesus and the circumstances, deleterious effects and adaptations for managing pipe flow that flips between open channel and full-pipe flow. Perhaps Smith would have considered this one of his "situation[s] to avoid" rather than "a problem to solve".

The choice of focus is not the only difference between Smith and Ortloff – they approach the subject of studying ancient technology quite differently. Ortloff's strength and expertise is hydraulic analysis, including computational fluid mechanics whereas Smith has familiarity with hydraulics, a more generalist engineering background and long experience of working in the history of technology. Given his background it is understandable that Ortloff offers a purely hydraulic explanation for all the design features he identifies and feels comfortable crediting Roman engineers with a more advanced hydraulic knowledge/awareness than is generally supposed. He raises the possibility that "ancient engineers possessed alternative ways of solving fluid mechanics problems by an as yet unknown or undiscovered methodology" (Ortloff 2009, p. 393) and believes that modern engineering analysis combined with archaeological evidence is the key to understanding not only the operation of ancient water technology but also the design intent and knowledge of ancient engineers. Smith (2007) is rather more cautious and circumspect in what he believes modern scholars can achieve. He discusses the difficulty of understanding the intentions of the ancient engineer and stresses the importance of considering the appropriateness and relevance of the questions that we use our modern tools to answer. He declares that “[t]here is a distinct limit to how far retrospective analysis can properly substitute deficiencies in conventional evidence” (Smith 2007, p. 10).

## 3.5 Summary

To face the broad and complex problem of understanding the water supply in Constantinople we need a wide range of tools. As explored in the introduction, we cannot hope to study the remains of the water supply rigorously and comprehensively – too much is hidden from view or has been destroyed by the subsequent development of the city. To overcome this problem, the first two sections of the chapter investigated the development of the technology available in the region at two levels: the individual element of the cistern and the supply system as a whole. The third part of the chapter took another angle, examining how the engineering perspective has been used to address archaeological water infrastructure problems.

Constantinople’s sophisticated cisterns are a culmination of all the development seen around the Mediterranean from the earliest Hellenistic homestead cisterns, through to the multi-chambered barrel-vaulted municipal Roman cisterns with increasingly sophisticated inlet and outlet arrangements. Pliny and Vitruvius were wary and cautious about using cisterns for water supply but the need for water storage to support larger populations, higher volume demands or settlements in more arid areas, led to adaptations in design to improve water quality. Every settlement shares the common experience of securing a reliable water supply. Reviewing the arrangements in Pompeii, Ephesus, Carthage, Barcino, Petra, Thessaloniki and Rome has revealed that each system served the needs and made use of the unique resources and constraints of its particular locality. Each place had to make decisions about what water source to use, whether this was local groundwater, rainfall or a distant spring, how to transport water to the settlement, arrange distribution and access to water within the settlement and how to control and manage the available water for the local demands. Each location made use of a similar set of components – aqueducts, pipes, castella, cisterns and fountains – to suit the local conditions. As the conditions were partly a function of the physical landscape, and the constraints created by landscape are still a factor of modern engineering, this can serve as a point of connection for the modern engineer when they consider the water supply on an ancient site.

Engineers have considered the engineering of ancient water supply before and reviewing this work has demonstrated that for the conclusions drawn to be of use to the archaeological community care must be taken when selecting the questions to ask and the methods for answering them. Typically, engineering studies focused on analysis of small portions of the water system because of the need for precise data to complete calculations. When considering a wider scope of water supply (Ephesus and Petra, both by Ortloff) the approach tended to combine the same detailed analysis of smaller elements with description of the whole system. Overall, the engineering studies tended to be more useful and persuasive when the hydraulic analysis was tempered with practical considerations of construction, as Smith does.

# The need for an engineering perspective

Tackling an intractable problem – broadening the engineering horizon – modifying modern design standards and performance criteria for an earlier age – what a model can tell us

## IV

> “Scientists discover the world that exists;
> engineers create the world that never was”
>
> Theodore von Kármán

## 4.1 Introduction

This chapter addresses a key question: how can an engineering approach be usefully used under the circumstances of this project? It has been established that the evidence of Constantinople's water supply is fragmentary and also that engineering investigations into other ancient water supplies (where evidence is also fragmentary) have been limited to portions of the system where adequate data allows hydraulic analysis. But this project has been framed to consider the water system on a city-wide scale. Without data for the whole system, how can the research proceed?

Engineering research may typically confine itself to a positivist perspective but in engineering practice working towards a practical solution using incomplete and imperfect data is normal. It is possible to use the expertise of engineers as designers to reimagine the water supply and in doing so, generate knowledge about it.

With Constantinople there is a seemingly intractable problem: enough of the Byzantine water supply remains to show that it was complex and is worthy of further study but there does not seem to be sufficient evidence to accurately characterise the water supply and answer the big questions – how was water distributed? Why were the open-air cisterns so big? How were decisions made about when and where to supply water? What was the driver for supplying so much storage within the city walls? Trying to understand the water supply combines the technical complexity of a city-sized infrastructure system – the speciality of engineers – with the impediments of fragmentary evidence and a 1500-year gap – the natural domain of archaeologists. How can engineers compensate for the lack of available data on the water supply system?

Many of the questions about Constantinople's water supply system, whether about the system as a whole or about individual elements, can be best investigated with a holistic understanding of the full working system. But consideration of the whole system requires a whole system to consider and in Constantinople there are only a few pieces left. To address this the first step is to recreate or reimagine the water supply. Using the elements that are left as a base, I will design a water network that *could* serve the city. In creating the design, knowledge will be generated about the likely problems faced by the engineers at the time and a working model will be established that can serve as the foundation of future research into the city and its water supply. The design will be developed from a modern design framework for water supply, taking into consideration inflow, distribution and demand and will be based on a set of performance criteria that are established below in Section 4.3.2. The purpose is not a detailed hydraulic design of the system – the level of detail and data required is not appropriate at this stage – but rather a higher level strategic design, investigating how sufficient quantities of water could be distributed and stored in order to satisfy the demands of the population. An agent-based mass-balance simulation of the system will then be used to assess the success of the proposed design. As alluded to in Section 3.5, there is a risk of over-relying on a modern frame of reference, which can lead to the wrong questions being posed and misguided conclusions being made.

## 4.2 Research Paradigms

### 4.2.1 Traditional Engineering Research and its problems in this case

The prevailing approach to research within engineering is aligned with the scientific method, with an independent observer building a hypothesis from what can be measured and then testing it (for instance Thiel (2014) argues that the only difference between the scientific and engineering approach should be the consideration of practical and human-centred outcomes). The positivist approach uses adherence to the concepts of independence, verifiability and replicability to give integrity and validity to the results. This approach is well suited to expanding knowledge in some aspects of the engineering sciences such as fluid dynamics, materials and thermodynamics.

This approach is typically what was used by the engineers discussed in Section 3.4. Chanson builds scale models reproducing what has been measured on site which allows him to test the behaviour of the structure at different flow rates and from the results he is able to determine likely maximum flows. Blackman's hydraulic analysis relies on having sections of channel complete enough in the 1910s for detailed survey measurements to be taken. The hydraulic analysis enables him to test whether there is an association between water depth and channel width. He presents this result as evidence that the Romans had no reliable method of predicting flow behaviour. Haut & Viviers confine their consideration to a section of the wider system because it is accessible and measurements can be taken (the routes and destinations of the channels outside the boundary of their study are not clear). Although the positivist approach can be used to defend the credibility of the results, it does this by constraining the questions that can be answered and, as with Haut & Viviers's results on efficiency of pipelines, it does not guarantee the relevance or value of the questions that have been answered.

In none of the cases considered in Section 3.4 did the engineer consider the water supply system as a whole. Ortloff does provide comprehensive descriptions of both Petra and Ephesus but this is done only through breaking the system into various parts and examining some analytically and others descriptively. Chanson (2000, 2002), Blackman (1978) and Haut & Viviers (2007) confine their investigations to single elements or small sections of much larger systems. Smith (2007) also largely focuses on a single component that is common across a number of systems. The decision to limit the investigations is largely bound up in the need for data to support the analyses undertaken. If this approach was used to explore Constantinople's water supply, progress would be limited – very few pieces of the puzzle remain, those that do have often been altered and adapted over time, and none of the pieces are physically connected to each other. There is little that a strictly analytical approach can add to what is already known.

### 4.2.2 A brief overview of research approaches in archaeology

In archaeology the aim is to learn about the past using what can be found in the present. Although the 'past' covers an enormous range of time, from the earliest human cultures to the medieval and even more recent times, the underlying difficulty in all cases is how to reasonably bridge that gap between the present and the past. What is available as evidence in the present varies significantly, from just a few fragmented pre-historic artefacts to, in recent history, more substantial remains and contemporary texts. More data and particularly textual sources can make bridging the gap to the past more straightforward and the results more secure, yet interpretation is still required. That act of interpretation from present data to understanding of the past is guided by theory. When considering the early history or pre-history periods, where archaeological evidence is sparse and unsupported by textual context, theory is more obviously fundamental in developing understanding and explaining the patterns and changes seen in the evidence. For the archaeology of more recent periods, which includes this project, theory can appear to play a less critical role, in part because of the greater volume of evidence, including texts, that can provide a broader platform for explaining and contextualising changes and developments (Johnson 2010, p. 18-20). In addition, there remain some who (incorrectly) believe that archaeology can be atheoretical, that is they believe they can 'let the data speak for itself'; however, as Johnson (2010) argues, all archaeology is shaped implicitly or explicitly by theoretical stances. Therefore, it is important to understand how you are moving from a particular dataset to a specific explanation.

Theory sets out the priorities and types of questions asked as well as proposing the acceptable ways of answering those questions. Very broadly, archaeology and archaeological theory has developed in a number of stages. Prior to the 1960s, culture-historical archaeology was typical, with a focus on defining cultures using similarities and differences in collected material. In the UK and USA in the 1960s, dissatisfaction with the traditional forms of archaeology led to the development of 'New archaeology' (later known as processual archaeology) which questioned the extent to which the 'archaeological cultures' developed under the culture-historical approach could be equated to the people living at the time. It sought to change the focus of inquiry away from the physical evidence and towards the people that produced the material, and to change the mode of inquiry to something more scientific. Developing a more scientific approach was seen as important for moving the understanding of the past forward (there was a view that the culture-history approach only led to increasingly detailed sequences of dated material and cultures, but did not offer a clearer understanding of the past). Postprocessual archaeology developed in the 1980s and 90s and is a collective term covering a number of distinct approaches that respond to criticisms of processual archaeology. Questions were raised concerning the ability of processual techniques to definitively test or prove the hypotheses put forward and there was an increasing awareness of the implicit assumptions involved in engaging with and assigning meaning to archaeological material and an acceptance of the need to consider the thoughts and values of the past. Today, archaeological theory is moving beyond the oppositional frameworks of processual and postprocessual traditions towards a number of approaches that cut across traditions and incorporate more nuanced understandings of many aspects of the earlier traditions.

In the case of this project there is, relatively, a lot of data available to us in the present. There is enough to enable a focus on the water supply of the city. This focus makes possible the assumption that the skills of the engineer are relevant and useful in engaging with the data. The project will not be based on the collection of new data in the field but rather on existing data that has been collected and described (that is, interpreted) by a variety of archaeologists. In general, I have accepted the interpretations made at face value but there are some exceptions (notably the structures found beneath the Mese) where I feel an engineering interpretation casts doubt on the archaeological conclusions about the data.

Whereas some of the other engineers involved in archaeological investigation have used a generally positivist approach to increase the richness of the data in the present (for instance, the CFD analysis of the “room of visit” structures and pipelines by Haut & Viviers), this study seeks to do more of the bridging work into the past, interpreting the data of cisterns, channels and landscape with an engineering perspective. To look at how this can be approached, we now move to engineering approaches and particularly the role of design in problem solving.

### 4.2.3 Engineering Design, Action Research and Systems Thinking

Although engineering research tends to be focused on a scientific mode of enquiry, assuming positivist principles, this approach, as discussed above, can be restrictive and is not sufficient to answer all engineering problems. The broader engineering discipline outside research accommodates a wide range of approaches that engineers can adopt to suit the needs of each particular project.

This reflects the underlying purpose of engineering which is generally focused on the creation of a solution to a stated problem rather than purely scientific work where the focus is more on explanation and the discovery/determination of new knowledge. Engineers harness the rigour and analysis of scientific thinking and integrate it with the holistic and contextual perspective of the designer in order to create social and economic value (Figueiredo 2008). They are pragmatic doers who emphasise doing what it takes to overcome complications, and judge the success of the outcome on the completed solution, rather than the method of getting there. This more open stance allows a wide variety of problems to be tackled successfully.

In this case we are investigating what an engineering perspective can do to transform the understanding of the evidence of the Byzantine water supply in Constantinople. In engineering, work is not directed at the creation of knowledge or enhancement of understanding but both are the inevitable result of engaging in a problem to develop a solution. In practice, engineering has a dual character, both using and creating knowledge when engaged in problem solving, expressed by Vincenti as:

> *"Engineers spend their time dealing mostly with practical problems, and engineering knowledge both serves and grows out of this occupation."*
>
> (1990, p. 200-1)

Vincenti makes an important point about the growth (or creation) of engineering knowledge. His 1990 work *What engineers know and how they know it* describes aeronautical engineering and the design of aeroplanes. The primary aim in designing aeroplanes is to solve the problem of flight, but within that work there are a number of sub-problems that must be overcome to achieve this primary aim. These problems only become apparent through the design process. For example, the need to create a new way of riveting thin metal plates in order to reduce drag. Participating in a design process not only creates a functional solution but also ancillary knowledge in the form of steps towards that solution. This two fold nature of engineering design, that it works towards a goal and generates detailed knowledge in doing so, means that it has rich potential as an area of research alongside more traditional, scientific methodological approaches.

Engineering design has similarities with research modes originating in other disciplines, such as Action Research, and these are beginning to be brought into engineering (see especially Cunha and Figueiredo (2006) and Figueiredo and Cunha (2007) on using Action Research and Soft System Methodology in Information Systems). The systems approach and systems thinking which have moved in the other direction, from an academic field into practical civil engineering (see Blockley and Godfrey 2017) help to articulate and validate many of the decisions and actions taken in the design process in this project.

A central principle of Action Research is that the researcher engages with the problematic situation to both improve it and increase knowledge about the subject (Dick 2000). The process is cyclical – reappraisal and reflection between cycles of action allow refinement and acquisition of knowledge. In the case of Cunha & Figueiredo (2006), a growing dissatisfaction in the traditional methods of information system design led Cunha to develop a new method using an action research approach – by engaging in a number of real design projects for clients he could explore the common issues encountered and test the effectiveness of proposed solutions. Cunha's initial work was not directed by Action Research, but it (A-R) helped to shape the later stages and was key to legitimising the process he had fallen into quite naturally (as a trained engineer) and allowed him to address the issues of generalisation, relevance and rigour that were fundamental to producing an acceptable PhD thesis. There are similarities between action research and this study but here the focus is on a single site (that is a single cycle of investigation, action and reflection) therefore there are not the same opportunities to borrow Action Research's accepted methods of providing valid and legitimate results.

In their consideration of systems thinking for infrastructure design, Blockley & Godfrey (2017) argue that engineering practice is governed by 'practical rigour' rather than scientific rigour. Whereas the idea of scientific rigour has been developed to regulate the search for 'strict truth', practical rigour must accommodate the realities of the open, complex world. To do so, practical rigour incorporates seven elements (Blockley & Godfrey 2017, p. 117). Although this list has been formulated with reference to the work of creating modern engineering infrastructure, it is also relevant to the work in this study and is included in full in the next section with discussion of how it applies here.

At this point it is worthwhile to return to the quote from Theodore von Kármán that opened this chapter:

> *"Scientists discover the world that exists; engineers create the world that never was."*

The present study is an investigation of something that did exist in the past but no longer does. I have argued that it is not something that is there to be definitively discovered in a scientific way. What that leaves as the proposed way forward is to create something that never was. As discussed above the process of engaging with a problem and trying to solve it generates knowledge and a deeper understanding of the problem and how it can be solved.

## 4.3 Proposal – a reimagined system

By engaging the approach of engineer as designer rather than as scientist, it is possible to be in a position to move the project forward. The pieces of the puzzle are no longer just elements to be analysed, but also indicate the wider system. Accepting that there is a wider system that was functional, an engineer can then begin to fill the gaps.

The project is centred around the design of a network capable of using the storage of the cisterns to distribute sufficient water to the population of the city. Figure 4.1 gives an overview of the process: the remains of the original system will be incorporated into a re-imagined system using engineering judgement and secondary sources of information such as the landscape of the city, textual descriptions and contextual knowledge of the technology of the time. This network design will then be combined with assumptions on inflow and water demand into a working model of the water supply system. Knowledge is likely to be generated from these processes and the working model acts as a tool for investigation of specific questions on the water supply system.

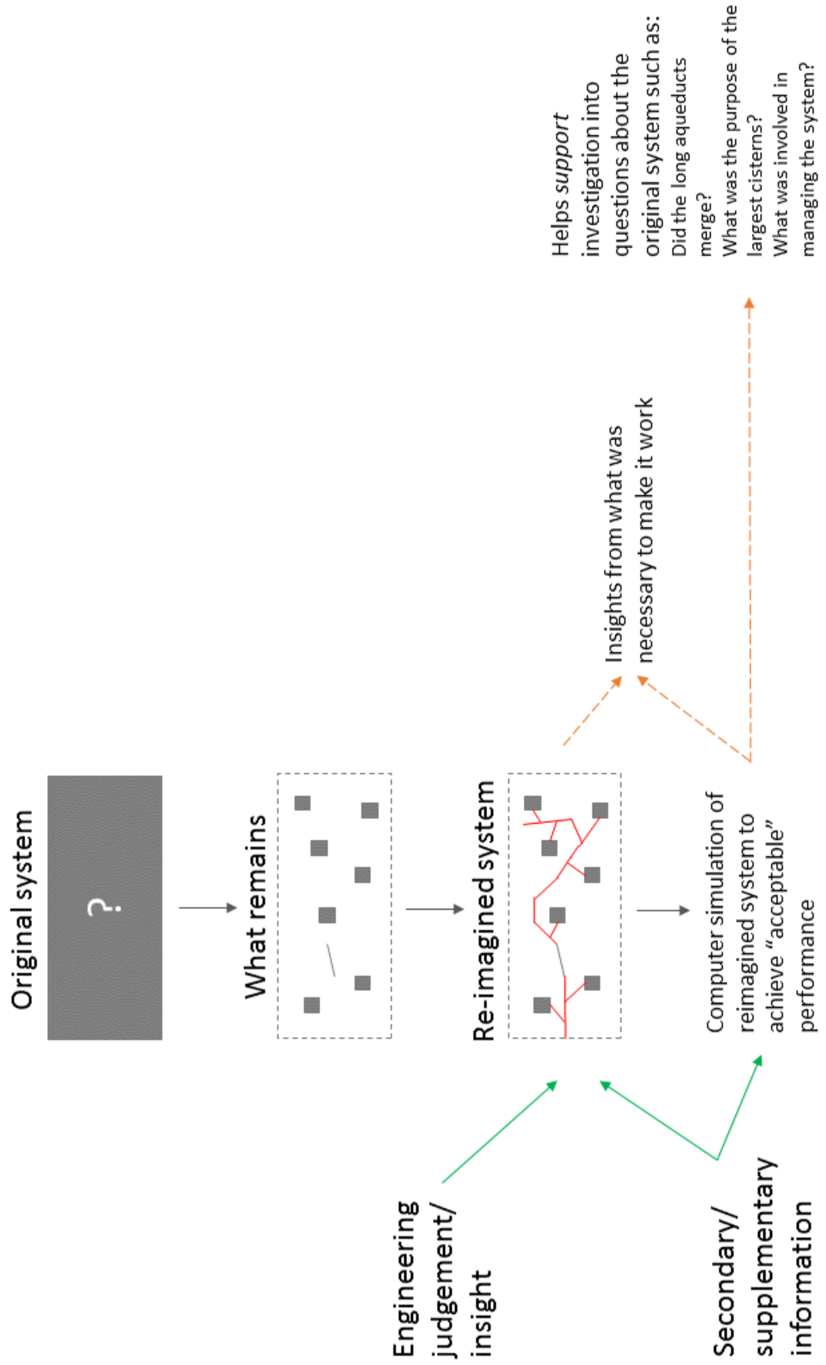


Figure 4.1: Overview of the engineering design process used to generate knowledge of the water supply of Byzantine Constantinople.

The validity of this approach is based on the assumption that it is possible for a modern engineer, if primed to imaginatively engage with the circumstances of the ancient engineer, to come to much the same conclusions and take the same view when dealing with the same situation. A key part of this is to separate the modern tools we now have from the fundamentals which are as valid now as they were then, for example whether to tunnel at Safalaan or go round a much longer route using a cut and cover method, would be decided on the same criteria today regardless of the advances in construction techniques. Whilst we cannot know the full context that determined the layout of the water supply network (for example very little is known about the road network (see Berger 2000) which is likely to have strongly influenced the position of pipework, channels and cisterns), we have both the physical landscape and pieces of the system (in the form of cisterns and channel remains) to guide our choices. This is not so much a design from scratch as a filling-in of blank spaces based on engineering judgement.

To ensure the study is valid, we can return to the concept of practical rigour given by Blockley & Godfrey (2017, p. 117) and its seven elements, shown here as adapted for this investigation of the infrastructure of the past:

1. *Making it work* – a satisfactory, functional solution is the objective in engineering and so reimagining the Byzantine system as functional is an insightful way to study it. (That is, it is appropriate to fill in the gaps to make a working system rather than confine ourselves to what is left.)

2. *Creating appropriate models* – Blockley & Godfrey state “the approximations of our models are the sources of practical rigour required to create a solution”. This is an acknowledgement that engineering work is situated in the real world and not everything can be known. Identifying what needs to be approximated or assumed in order to *make it work* informs design decisions and provides transparency for future work. Without initial models based on assumptions there is nothing for future study and refinement to be based on. The development of the reimagined model of the water supply is described in Chapters Five, Six and Seven.

3. *Considering the whole as well as the parts* – in opposition to the analytical approach of breaking down and isolating separate components of a problem, there is a need for practical rigour to include even the parts of the problem that are not well understood. Here this is embodied by the approach to move the work beyond the remains and create a model of the whole working system.

4. *Making judgements* – "Professional opinions are not arbitrary". In this case, professional engineering experience in water, drainage and infrastructure design is complemented with access to archaeological knowledge of Constantinople and its water supply.

5. *Exercising creative foresight* – in this case we need creative hindsight and the creativity to imagine what might have happened. Central to this is preparation to imaginatively engage with the context – developing an understanding of the technology of the time and purposefully stepping outside our modern engineering framework. Chapters Two and Three help to implement this element.

6. *Developing and evaluating dependable evidence* – this project relies on a range of evidence of varying dependability. Here we move away somewhat from the modern requirements. Our need for dependability is not to ensure safety when making construction decisions but rather to demonstrate the degree of confidence in the presented conclusions. In conjunction with point 2 above, we can proceed knowing that while more concrete evidence is more useful, it is not always available and approximations and assumptions will be necessary.

7. *Feedback and learning* –systems-thinking requires a mind open to feedback and learning. The mechanism of feedback and learning – iteration – links with several of the previous points: *Making it work*, *Considering the whole as well as the parts* and *Exercising creative foresight*. The potential complexity of feedback is significant in systems as it is not simply linear or reciprocal: a change in one part of the system may influence another which may influence a third and so on. Within the project this has required an awareness of the interaction between the

elements of the system, such as inflow, demand, and network connections and the actions necessary to fit them all together into a working whole. Rigour has also been ensured by preparing the project work to withstand external scrutiny through presentations, conference papers and journal articles.

### 4.3.1 Method

The design work will incorporate a modern engineering framework of what to consider, with the broader work to understand the city and its topographical and historical context. Although topographical circumstances will be used to guide the design, the aim is not to create a hydraulic model at this stage. Instead the design is high-level and focused on enabling the distribution of water resources.

#### Imaginative engagement creates appropriate conceptual models

Engineers may well create what never was but they do not create out of nothing. Design is guided, even at early stages, by conceptual models of plausible solutions (Pirtle 2010). That is to say that the engineering design does not emerge from nowhere but is shaped in part by the engineer's understanding of existing tools and technologies. Therefore, it is important that when developing a solution to an ancient engineering problem, the engineer is knowledgeable about the techniques and technology of the time. Chapters Two and Three have been an important part of the imaginative engagement in the time period.

#### Base data – spatial framework

Civil engineering projects exist at such a large scale that there is a direct interface with the landscape. The project began as any engineering project would, developing familiarity with the city and the available data, organising it spatially and reinterpreting some of the textual evidence (the *Notitia Urbis*) in a spatial format. As well as determining what was known, this exercise highlighted what was missing from the picture. This enabled the problem to be framed as the missing elements which pointed to a way of solving it: create a design for the water supply system that completed the picture. This initial work also created the base maps used throughout the project. The development of these maps is described in Section 5.2.

### Modern network design

The design process will make use of the modern framework of water supply design, accepting that this was not the way that the original system was created but has the same purpose – to get water to the people of Constantinople. Modern design seeks to balance the available water resources with the water demand and uses treatment, storage and distribution to ensure customers are able to access the water that they need. For this project, the system will be considered as three elements – the inflow or available water for supply, the means of distribution, and the water use or demand.

### Inflow

The inflow of water into the city determines the amount of water available to use. For Constantinople, water was directed from spring sources in the Thracian hinterland through the Aqueducts of Valens and Hadrian into the city. The Aqueduct of Valens is being considered independently in the parallel project on the water supply system outside the city and this project will use the results obtained for inflow. For the Aqueduct of Hadrian, little is known but the possibility of using information for the Ottoman era Kırkçeşme system is investigated. The potential for rainwater harvesting to be a main source of water for cisterns is also considered. Inflow is discussed in section 5.3. The quantity, variability and reliability are all factors that would have influenced the development of the water system and its operation and there are important questions regarding the arrangement of the different phases of the Aqueduct of Valens that will be considered in Chapter Seven.

### Demand

A modern water network relies on accurate models of water use and predicted changes in the future to determine how much water is required by the population to be served by the water supply system. The population served by a water supply can be complex with varying needs for domestic, commercial, municipal and industrial customers. Modern systems are able to forecast likely demand based on accurate mapping and established standard use models for domestic households and commercial premises and on a case by case basis for industrial usage. However modern use statistics are of little relevance to the ancient city and this is an area with little data or evidence to guide the design. There is a detailed discussion of the approach used to represent water demand, and its limitations, in Section 5.4. A water demand model is developed for Constantinople in terms of quantity and spatial distribution across the city. There is a great deal of uncertainty about the demographics of Constantinople but a population figure of 375,000 (for the 6th century) suggested by Jacoby (1961) is adopted and a distribution is proposed based on the *Notitia Urbis*. Other water use is considered but it is concluded that, with the exception of public baths, all water use should be incorporated into a single *per capita* value. Public baths are major water users and are considered separately.

#### Network

To design the distribution network, the known information is incorporated into a network of proposed channels and connection points. The intention is to begin with the elements about which most is known, then those with less evidence and finally those of which there is no evidence. The design takes into account the physical landscape of the city as one of the major factors to influence the design that still remains. Consideration is first given to the cisterns within the city, consolidating the most recent previous works. The cistern dating established by Altuğ is used to exclude cisterns that were constructed at later periods and data on cistern volume has been used where available to exclude cisterns smaller than 100 m$^3$. Next, the routes of the two main aqueducts, of which there is some but not comprehensive evidence, are reassessed to establish the core of the system. Finally, the connections between the aqueducts and the cisterns are considered. These connections must have incorporated control mechanisms, to facilitate the distribution and management of water through the system, although there is little evidence of the form these took. The development of the network is discussed in Chapter Six.

### 4.3.2 Purpose – a working model

The information on inflow, demand and the distribution network will be combined in an agent-based model. Within it a mass-balance type model which considers how water will be distributed and stored within the network, without taking account of the hydraulic aspects of the distribution system, enables the viability of the network and performance of the system to be explored. In the mass-balance model water enters the system and at each branch point a decision must be made about how to share the water, directing it towards a cistern to be stored or letting it pass further into the network. The population collects water from nearby cisterns to meet their daily needs and Public baths and the Imperial Palace take a daily allowance from the system. The decision made at each branch point about water sharing can be altered to vary the operating strategy and thus the performance of the model.

The working model is a useful tool for exploring different flow scenarios and management strategies. However, to do this we must establish a way of capturing the performance of the system. It can be difficult to understand and objectively measure how well or poorly a large complex system is performing. In modern water supply systems, functionality is assessed based on performance criteria. For example, Vairavamoorthy *et al.* (2011) give typical performance indicators as pressure, flow, water quality, service interruptions, leakages and pumping efficiency.

These modern examples are not particularly relevant for Constantinople, especially when we know so little about what the expectations of the population were with regards to water. I propose to use a version of service interruption – service failure – as the primary measurement of success within the model. It will be defined as an occasion when a person (or entity such as a public bath) fails to obtain the water it seeks.

For Constantinople to have flourished as it did, water must have been generally available but an account of the performance of the water supply in Procopius can suggest what an acceptable rate of service failure might be. When discussing the purpose for constructing the Basilica cistern, Procopius states that the city generally suffered shortages during the summer though at other times there was an abundance of water (Dewing and Downey 1940, p. 91). Many other texts throughout the period of Constantinople talk of the water supply in terms of abundance although there are also mentions of droughts as well. While these will be reviewed during model development, acceptable performance will be provisionally defined as:

- In the summer months (June – September) a service failure rate <10%; summer shortages were normal (at least up until the construction of the Basilica cistern – it is not clear whether this solved the problem), but were probably not the wide-scale droughts that led to queueing and fighting outside cisterns. It is difficult to put a figure on what would be considered a tolerable level of summer shortage. Initially the 10% service failure rate will be used, though it may need to be revised if it proves too difficult to achieve in typical summer conditions.

- In all other months (October – May) a service failure rate <1%; given that water was described as 'abundant' at times other than summer, it is reasonable to expect a very low failure rate.

- No failure of water to the Imperial Palace; the supply to the palace was protected by laws that restricted the use of the Aqueduct of Hadrian. Given the importance of the structure it is unlikely that shortages were tolerated, so a severe performance measure of constant supply has been used.

- No failure of water to the public baths during October – May; the public baths were major water users and centres of public life so during the seasons that water was abundant, it is unlikely that interruptions to service because of a lack of water would be expected.

- Fewer than five failures of water to each public bath per month during June – September; it is not clear what the hierarchy of priorities were for Constantinople. Vitruvius speaks of a *castella* design that maximises flow to the public fountains over baths and private supplies. Although a *castella* constructed to such a design has never been found, it is possible that the sentiment was encompassed by the water management strategy in Constantinople. If there were water shortages in the summer, it is likely to have impacted the supply to the public baths, yet they were such important part of life that would be maintained for as long as possible. An initial measure of 5 failures per bath per month during the summer season will be attempted.

The performance criteria are revisited in Chapter Seven which details the development of the model and the results obtained from investigating different operational strategies and examining the different arrangements for the different phases of the Aqueduct of Valens.

### 4.3.3 Limitations of the model

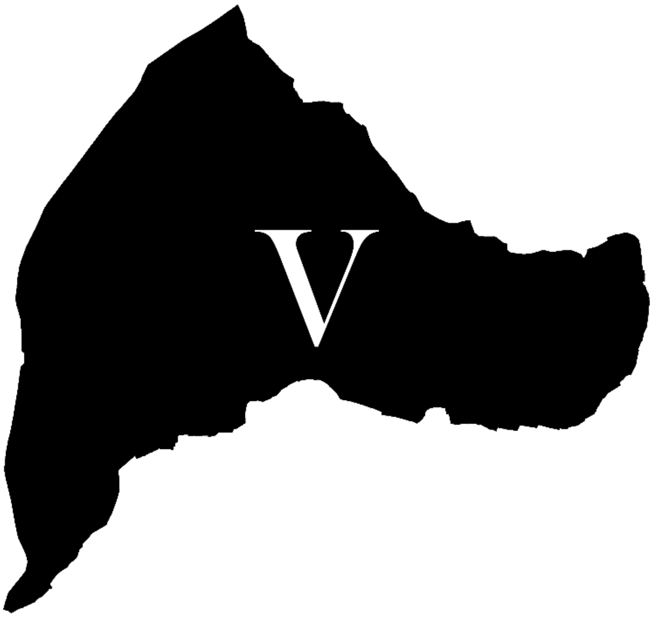
As discussed above, this model is not a definitive answer to how the water supply system worked. Figure 4.1 illustrates the relationship between the original system and the working model produced. It is necessarily based on approximations and assumptions, some of them based on dependable evidence, some on less dependable evidence. There is a great deal of opportunity for improvement and the model serves as a foundation for future studies and refinements.

## 4.4 Summary

The typical mode of enquiry in engineering research closely follows the scientific method. However, such an approach is not suitable for this project which requires a more exploratory and less experimental method. Engineering in the broader context outside research uses a variety of approaches to achieve its aim (usually solving the stated problem). With the focus shifted away from the importance of a method that ensures the rigour of the solution and towards finding possible solutions, the skills of the engineer as a designer become pivotal. As the engineer engages with the problem in order to create a solution, she creates new understanding and knowledge alongside the solution itself. This is appropriate in the case of the Constantinople water supply because the principal benefit is the increase in knowledge of the water supply system, with the model of a functioning water supply a useful tool for further investigations. The civil engineering behind any large infrastructure system is significantly influenced by the landscape in which it is situated. This is an advantage when studying ancient infrastructure: where the landscape remains relatively unchanged, it provides a source of evidence for the constraints faced by the engineers of the time. A modern engineer, stepping out of the framework of modern engineering, will make similar decisions to their Roman counterpart when faced with the same set of constraints and technology. The ability to use the available archaeological evidence with an engineering understanding of infrastructure systems is key to developing a system-wide model of the water supply of Constantinople. That system-wide model must integrate what is known and can be established of the water sources bringing water into the city, the demand for water from the population and the activities central to a bustling imperial capital, and the distribution network consisting of pipes, channels and cisterns.

# Reimagining the water supply system: inflow and demand

Mapping the city – quantifying the water flowing into the city – quantifying demand



## 5.1 Introduction

This chapter draws together the elements of the system that are not part of the physical network (which is dealt with in Chapter Six). In order to form a picture of the water system there is a need to be familiar with both the landscape in which it is set and such knowledge that has survived about it. Against this background, we can consider how water was brought to the city and the factors that influenced this and then reverse the perspective and assess how the water that arrived in the city was used. Considering the nature of the water sources, their number, quantity, variability and reliability can help to develop an understanding of why the infrastructure developed as it did. Equally, investigating the nature of water use within the city assists in the understanding of the infrastructure. As well as these broader benefits, determining suitable parameters for both inflow and water demand is important for the development of the system-wide model which will enable the operation of the water supply to be investigated.

To quantify the inflow into the city 1500 years ago is a major challenge; there are almost no records of even the modern spring flow and little evidence of how this might have changed over the preceding millennium and a half. For the Aqueduct of Valens, there is uncertainty about the number of springs that fed into the system, and little evidence of, or information on, the Aqueduct of Hadrian. Investigating the demand for water offers an independent check against the conclusions made about the inflow, for example, indications of a lot of water-dependent activity suggests a reliable and abundant inflow. However, as with the inflow, there are significant challenges with building a detailed picture of the water demand in 6th century Constantinople. Whilst there is general information on water use, the specifics are lacking. It is possible to infer from the evidence that Constantinople had a wide range of water users and apparently no major restrictions or reduced expectations for water use: for instance, there were numerous public and private baths and visitors repeatedly talked of the abundance of water within the city. Yet turning the evidence that relates to performance into concrete numbers has proven a challenge. A detailed consideration of the population and its distribution within the city offers the most promising method of usefully representing the water use of the entire city.

## 5.2 Mapping the city

Landscape and spatial understanding are critical factors when considering a civil engineering project and particularly a gravity-fed water system. Much of the initial work on this project was developing familiarity with the Byzantine city through the creation and development of maps. These maps were important not only to develop a topographical resource but also to provide the wider context of the city, for example, where people lived and worked (which would likely have a reciprocal relationship with the water supply) and where the major civic structures were (which would impact on routing of the water supply network). Developing the maps also clarified the gaps in knowledge that would constrain the project.

### 5.2.1 Ground levels

Key to generating a model of the system and improving the understanding of the water supply has been the gathering and development of a number of spatial datasets in ArcGIS. A 3-D digital model of the city was created by digitising the contours of Müller-Wiener's (1977) map of the Byzantine and Ottoman historical monuments in Istanbul. These contours, from the base map that Müller-Wiener used, represent ground levels in the 1920s which are generally higher than in the Byzantine era. Reconstructing the precise topography of the time is difficult because there are relatively few data, however, building on the work of Crow *et al.* (2008, p.110) there are three areas where the ground level is known:

- At the valley between Hills Three and Four (see Map 5.1), excavations around the piers of the Bozdoğan Kemeri revealed the foundations to be 6.5 m below ground level and the nearby St Polyeuktos church to be 3 m below ground level (Harrison 1986, Bozdoğan Kemeri – "Sounding B" p. 13-14, St Polyeuktos Fig G, Sections 32, 37, 38).
- At the Forum of Constantine on Hill Two, excavation around the Column of Constantine showed the cobbles of the forum to be 2.35 m below modern ground level (Müller-Wiener 1977, fig 288).
- On the platform to the south of Hills One and Two, excavations of the Hippodrome and Zeuxippos Baths revealed ground levels 4.5 m and 5 m

below current levels (Casson, Talbot Rice & Jones 1928, p. 8) and at the northeast edge of the platform excavations of the Great Palace put the ground level at 2.8 m below the modern level (Mamboury & Wiegand 1934, p. 35).

Using the reference points, the contours in these three places were reshaped to better reflect the reality during the Byzantine period. Ottoman terraces constructed around the top of Hill Three indicate that it has been extended to support the first Ottoman palace (Eski Saray) then the Süleymanie Mosque to the north;[36] the hill has been reshaped to 'remove' this work and lower the ground to position the cistern beneath the Children's Library (currently more than 3.5 m below ground level) closer to the surface. These alterations, highlighted in Figure 5.1, affect only small areas of the whole city. It is recognised that the contours used are a hybrid of modern and probable Byzantine ground levels, however, the areas that have been altered are all critical when considering the water supply.

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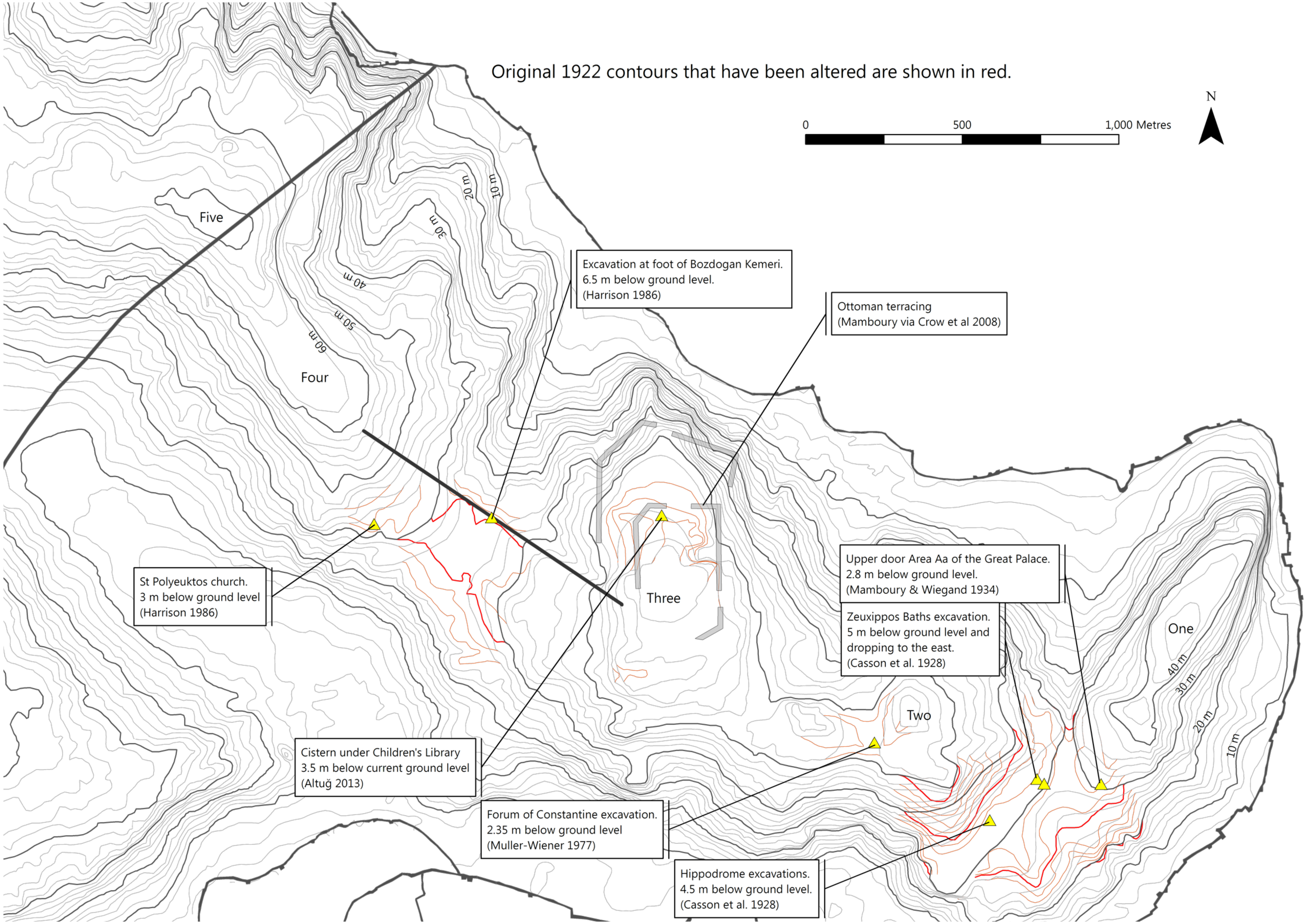
[36] These terraces are included in Crow *et al.* 2008, Maps 12-15 and originally come from a map by Mamboury that was published in Janin (1964).



Map 5.1: Alterations to the modern contours based on archaeological evidence to better represent the likely ground levels (at key points) during the Byzantine era.

### 5.2.2 Context of the city

Equally important to understanding the landscape that influenced the development of the water supply are the remnants of Byzantine buildings and infrastructure that can help define the boundaries of the city and give us an indication of how it functioned. This indicates where the aqueducts and other water supply infrastructure were likely to be placed. Müller-Wiener (1977) provides the line of the sea and land walls that mark the boundaries of the Byzantine city and the main landmarks in the city: fora, columns and churches.

The regions detailed in the *Notitia Urbis* are key to forming a picture of how the city was organised. For each region, a brief description of the landscape gives an indication of the boundaries with reference to buildings and structures (Matthews 2012). This allows an approximate layout of the regions to be established, (see Chapter 2, Figure 2.8). Map 5.2 shows the distribution of amenities and major public structures across Regions I-XII. The amenities shown are public and private baths, public and private bakeries, *gradūs* (which are the distribution points of the *annona*, or free bread), porticoes (also called *stoai*) which would house many types of shop and commercial premises, warehouses and markets. The position of each element in Map 5.2 is not definitive,[37] unless there is evidence to support it – for example, the Zeuxippos Baths. The position of other elements is based on the topography and infrastructure of the Byzantine city. For example, all baths are positioned such that water would be available – note that Region XII's five private baths are clustered on the lower slopes of Hill Three, where water could be accessed, and avoid Hill Seven, which had no reliable water supply until the early 6th century. Public baths, which would have been extensive, are positioned to avoid the steeper areas of the city. Similarly, many of the porticoes are positioned along the line of main roads, such as the Mese, and warehouses are assumed to be in close proximity to the harbours. For elements with no evidence of location and where the topography and known infrastructure cannot refine the location – such as *gradus* and bakeries – the positioning within the region is random. The *Notitia Urbis,* represented in Map 5.2, gives an impression of life in the early 5th

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[37] See Mango (2000) for discussion of the distribution of porticoes, Mundell Mango (2000) for the distribution of warehouses and Mundell Mango (2015) for public and private baths.

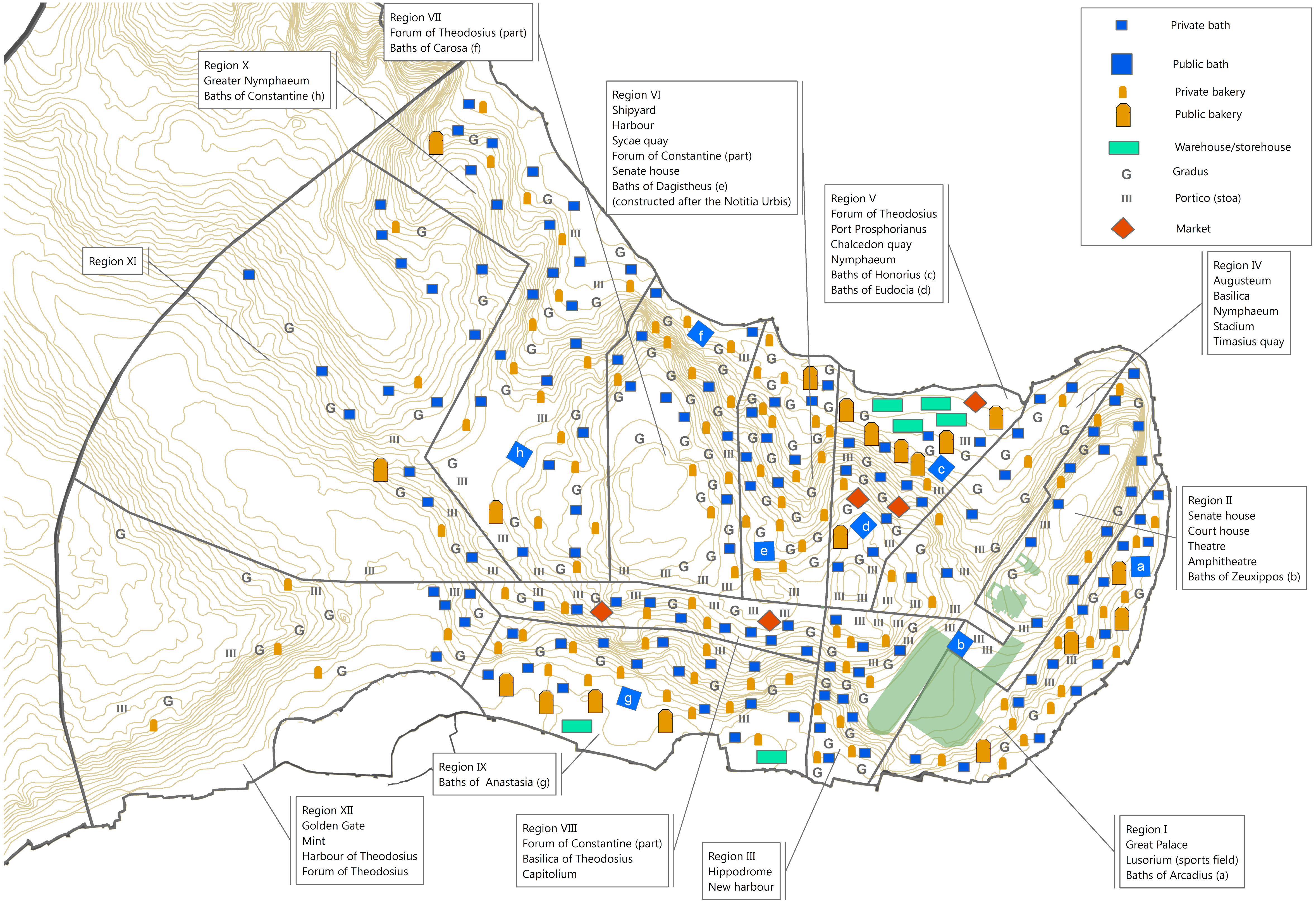
century, with amenities spread across the city, being particularly dense in the older parts, whilst the outer Regions X, XI, and XII show room for future growth. As would be expected with a major city, business thrived throughout the city.

### 5.2.3 What we still do not know

We are unable to accurately place a number of important features on the map of Constantinople. Perhaps most critical to this study of the water supply are the locations of the large public baths or *thermae*. The *Notitia Urbis* lists seven *thermae* within the city walls: one each in Regions I, II, VII, IX and X; and two in Region V (Matthews 2012). Another, the Baths of Dagistheus was added in the sixth century (Mundell Mango 2015, p. 140). But of these eight, the location of only two are known and only one of these (the Zeuxippos Baths, excavated in the 1920s) is known definitively. For the other public baths, as only the region is known, they have been placed on Map 5.2 with consideration of the topography (steep slopes avoided) and access to the water supply.

In addition to major water users, some cisterns and nymphaea are not located precisely. The location of the Arcadius cistern and the two smaller nymphaea are only known in general terms (respectively, Regions XI, IV and V). Some locations are possible but not certain: the Modestus cistern (Region XI) is associated with the remains of a structure that was observable in the late-19th century by Forchheimer & Strzygowski (1893, p. 52), and the Cistern of Theodosius in Region V might be the same as the Cistern of Philoxenus, identified by Bardill (1997) as the large open-air cistern at the peak of Hill Two. The only evidence of smaller baths has been found at Kalanderhane, next to the Bozdoğan Kemeri and in the grounds of the Archaeological Museum on Hill One (Mundell Mango 2015, p.138).

In a more general view of the city, the layout of streets is uncertain beyond the main street, the Mese, which ran from Forum Tauri, through the Forum of Constantine and on to the Hagia Sophia. The *Notitia Urbis* does give the number of streets for each region but these are difficult to interpret, ranging from only seven in Region III to 85 in Region VII. Berger (2000) suggests a street layout using buildings, foundations and cisterns as guides but, outwith the major monuments of the Hagia Sophia, Palace and Hippodrome, only 13 points are used to extrapolate an angular grid that takes no consideration of the topography.



Map 5.2: Map of selected details of the *Notitia Urbis*, illustrating the distribution of baths (public and private), bakeries (public and private), *gradūs, stoai*, warehouses, markets and key public structures. The map represents the density of amenities noted for each region and does not claim to place elements definitively. With the exception of Zeuxippos Baths, where the location is known, elements are positioned on the map using the topography and known infrastructure as a guide. For elements with no evidence of location and where the topography and known infrastructure cannot refine the location – such as *gradūs* and bakeries – the positioning within the region is random.

## 5.3 Inflow

The source of the city's water supply is the fundamental component upon which the entire system is based. As discussed in Chapter Two and illustrated in Figure 5.3, there are three known constructions that bring water into the city: the Aqueduct of Hadrian, which predates the city of Constantinople and draws water from the Belgrad Forest; the 4th century phase of the Aqueduct of Valens, which draws water from two springs at Danamandıra and Pınarca; and the 5th century phase of the Aqueduct of Valens, which draws water from Pazarlı and other springs. The enormous lengths that Constantinople went to in order to secure the sources tapped by the Aqueduct of Valens show their importance to the city and suggest a scarcity of suitable water resources in the region.

Understanding the amount of water that arrived at the city is a complex matter influenced by a number of factors that interact. On the one hand, there is the volume of water produced at each spring and it variation over the year; on the other, there is the channel, which by its cross-section and gradient controls how much water can be passed forward at each point. Therefore, to get a more plausible account of the inflow to the city, the spring yield and conveyance to the city must be considered together. The level of detail to make such a consideration is only available for the Aqueduct of Valens. For the Aqueduct of Hadrian, the evidence is too incomplete to estimate the likely flow but observations of flow in the Ottoman Kırkçeşme system can be used as a proxy. Alongside the known aqueducts there are two more possible sources of water to consider – rainfall as a major source (rather than just a supplementary source that is exploited where it is expedient to do so) and water from the Halkalı springs which formed an important part of the Ottoman water supply system.

### 5.3.1 Aqueduct(s) of Valens

The water flow of the Aqueduct of Valens has been studied in detail by F. Ruggeri (2018, PhD Thesis). This section is a summary of that work as it relates to this study and is based on the output of HEC-RAS modelling that she has kindly provided (Ruggeri provided the data on which Figures 5.2, 5.3, 5.4 and 5.5 are based). The key question impacting the inflow to the city is the arrangement of the fourth and fifth century phases of the aqueduct (see Map 5.3). Upstream of Kalfaköy, evidence has been found of both the wide fifth century and narrower fourth century channels running alongside each other (Crow, Bardill & Bayliss 2008); downstream only a narrower channel has been found. Either the fifth century line was constructed in parallel to the fourth century line all the way into the city and the evidence of the channel has been lost[38] or, at some point downstream of Kalfaköy, the fifth century channel fed into the fourth century channel such that all the water from the Aqueduct of Valens arrived in a single narrower channel (Crow 2012, p. 41). Whether the channel merges or continues separately has a profound impact on the amount of water that could reach the city. At first merging may appear to be an unreasonable suggestion: the initial joining (whilst, presumably, maintaining a flow into the city) would have been a technical challenge and a single narrower channel clearly has a lower capacity than the narrower channel and a broad one together. However, there are potential advantages in terms of reliability of flow: the constriction of the narrow channel would control how much water could pass forward and cause excess water to back up within the channels, which would act as a form of reservoir, continuing to discharge at a steady rate for a period after the inflow had dropped. This could result in a typically smoother and more consistent flow arriving in the city, which may have been easier to manage. On the other hand, that reliability is at the expense of additional inflow volume which is conveyed part of the way towards the city then allowed to spill at the joining point. This extra volume, if it reached the city, could be vital for refilling cisterns at times of shortage.

Building on Çeçen (1996a), Crow, Bardill & Bayliss (2008) and Snyder (2013), Ruggeri has reconstructed the line of the aqueduct, combining observations from over a decade of fieldwork by the team from Newcastle University led by Crow, with satellite data of the Thracian countryside. This enabled the length of the system to be updated and a detailed profile of the gradient and width of the channel to be established for the first time. In order to explore the hydraulic

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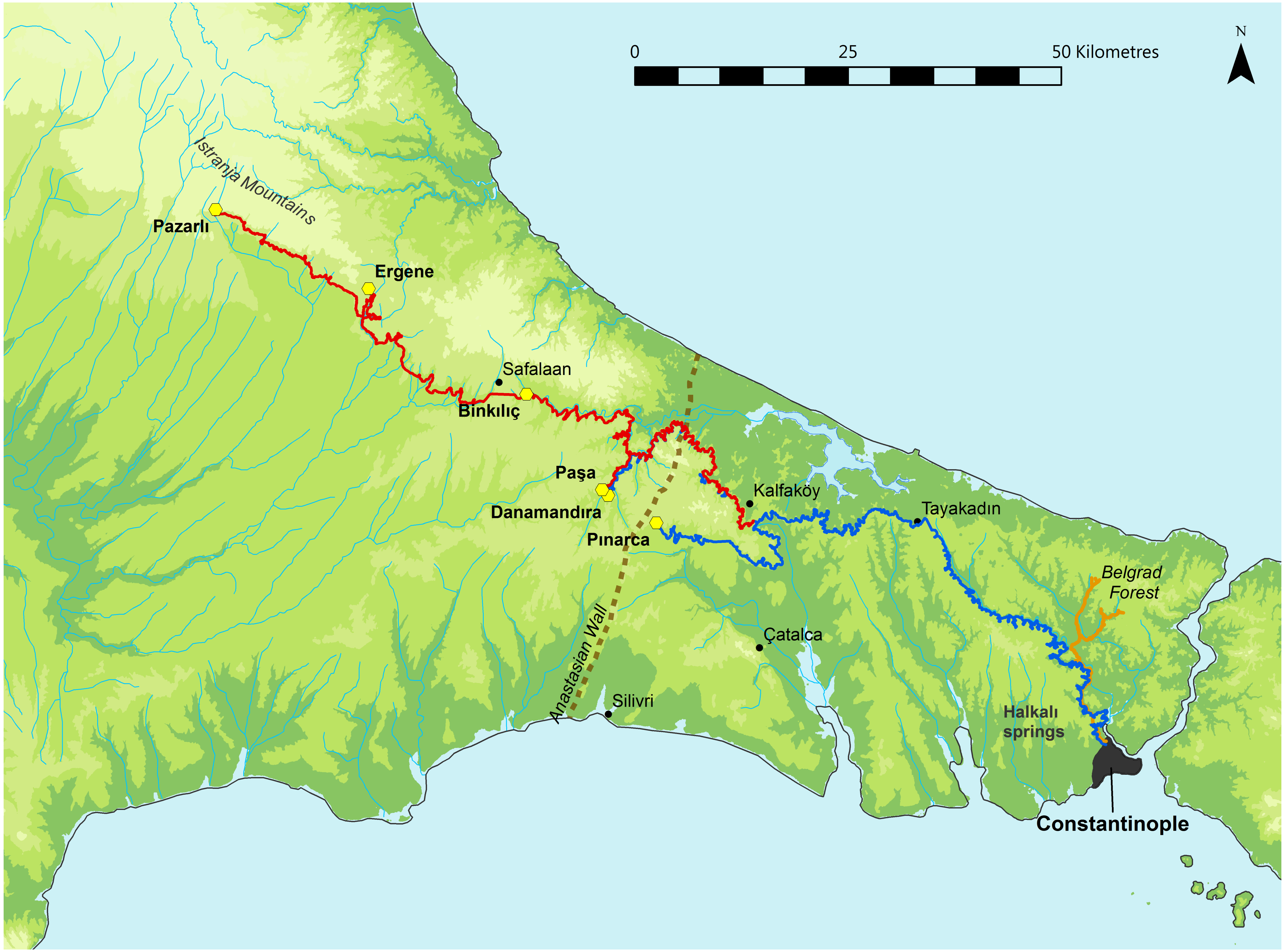
[38] Observations of the narrower channel are much sparser in this downstream section. There has been a great deal of development associated with the growth of Istanbul which may have covered or destroyed evidence of the channels.

behaviour of the aqueduct channels, Ruggeri investigated the spring flows that fed the Aqueduct, identifying six (see Map 5.3): the two known springs (Danamandıra and Pınarca) that feed the two legs of the fourth century channel and two known (Pazarlı and Ergene) and two assumed (Paşa and Binkılıç) springs that fed into the fifth century channel. Determining the flow from these springs into the aqueduct is challenging: the springs are in a karstic limestone environment which can result in unpredictable, reactive spring flow which is difficult to model accurately; Istanbul's modern water supply extracts water from the spring areas closer to the city so the springs no longer reach surface level; and it is impossible to establish how the springs behaved in the Byzantine period and how they were exploited by the Byzantines.



Map 5.3:Aqueducts for Constantinople in Thrace: Aqueduct of Hadrian (orange), 4th century Aqueduct of Valens (blue), 5th century Aqueduct of Valens (red); spring sources Belgrad Forest, Halkalı, Pınarca, Danamandıra, Paşa, Binkılıç, Ergene and Pazarlı. Map drawn by Francesca Ruggeri with adjustments by the author.

Having first established through macrophysical climate modelling (MCM) that the rainfall of the early Byzantine period was similar to the modern era, Ruggeri used modern monthly spring yield data for Pazarlı to create a number of scenarios that could represent how the aqueducts carried water to the city. The Pazarlı spring data was adapted for all the other spring sites (none of the others had been studied), assuming that each would have a similar relationship in terms of depth of the channel. For example, if the spring flow at Pazarlı in April was sufficient to half fill the channel there, then it was assumed that the channel at Binkılıç, although a different size, would also be half full in April.

When considering management of the network within the city, monthly figures are of limited use as cistern capacities are in many cases small and could be filled in a few hours by the flow in the aqueduct. If the springs were highly reactive to rainfall, inflow into the city could vary considerably not just across a month but also hour to hour, which would require a management strategy different from that needed by a non-reactive spring providing a more consistent, smoother changing flow. By considering the monthly average figures to represent one extreme of spring arrangement – where the spring has very low reactivity to rainfall, essentially a slowly changing base flow, it was possible to conceptualise the opposite extreme – a spring that is extremely reactive to rainfall, creating a highly variable inflow into the system. To create the highly reactive springs Ruggeri used the rainfall records from three weather stations (representing the different locations of the six springs) to scale the monthly average flows into a series of storm peaks. A third characterisation of the springs was created as a middle ground between the non-reactive and highly reactive springs: springs that do react to rainfall events but to a lesser extent than the very reactive spring and have a higher base flow than the highly reactive spring. The constructed spring flows were then entered into a HEC-RAS model of the aqueduct which simulates the conveyance of the water and the associated attenuation, constriction and losses to create an output of the water reaching the city.

The output has been prepared for four year scenarios developed from modern rainfall data: Year One is considered to represent a low flow year, Years Two and Three have average flows and Year Four is a high flow year. Figure 5.1

considers the total volume of water delivered to the city in a year for each scenario. Several points can be considered from this graph: there is a clear advantage in terms of volume delivered in the parallel scenario; the average flow years have around 50% increase in volume and the high flow year over 80% increase in every scenario. However, the low flow year has a much more limited increase: 23% in the highly reactive scenario and only 7% in the non-reactive scenario.

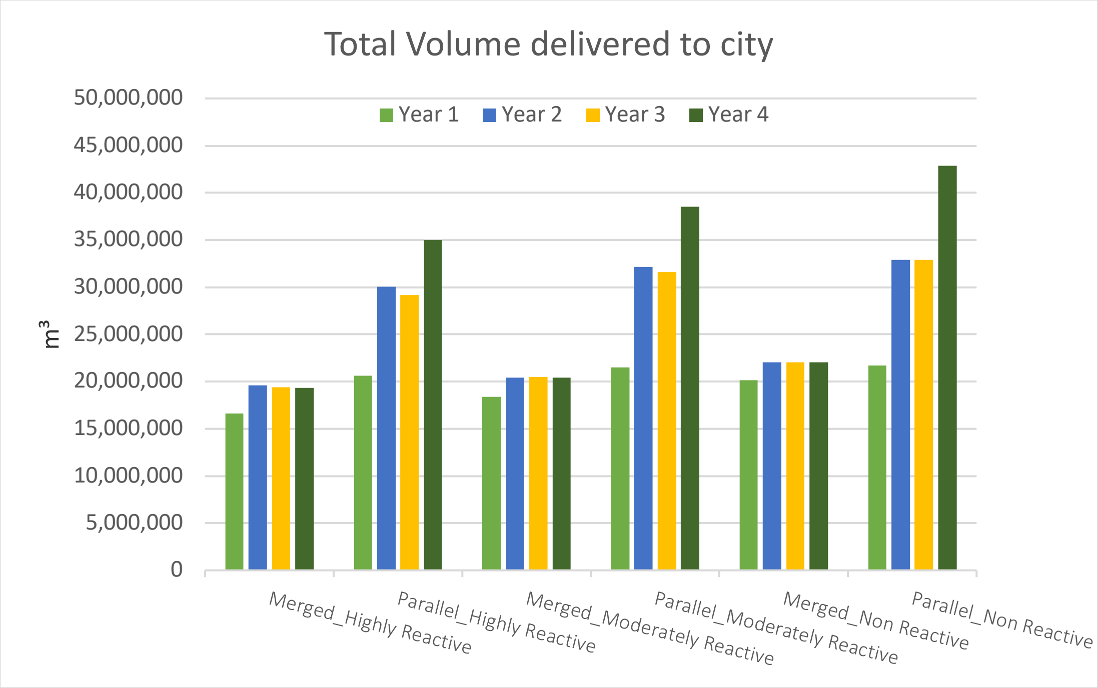


Figure 5.1: Total volume of water reaching the city for different spring reactivity (highly, moderately and non-), channel connectivity (merged and parallel), and rainfall records (Year 1: low, Year 2: average, Year 3: average, Year 4: high).

The merged scenario delivers less water to the city but it also creates more consistency between years, with the relative change between average and high flow years and the low flow years much smaller than in the parallel scenarios. Consistency may have been an advantage in terms of planning and management of the system but it would have been provided at the expense of significant quantities of wasted water, shown by the difference between the merged and parallel values for each scenario.

Figure 5.1 also illustrates that the reactivity of the springs has some impact on the volume delivered. The more reactive the spring, the lower the total volume conveyed all the way to the city. This is because the more reactive springs have high storm peaks that can exceed the capacity of the channel and will be lost as spillage; the less reactive springs have a higher base flow and lower storm peaks so are less likely to overwhelm the capacity of the channel, resulting in a higher proportion of the total inflow reaching the city.

Figure 5.2, Figure 5.3, Figure 5.4 and Figure 5.5, below, show the output of the HEC-RAS model (or inflow to the City) for the four years with the six different scenarios: highly reactive, moderately reactive and non-reactive springs in both the merged and parallel aqueduct channel scenarios. Each will be used as inflow in the model of the city network (discussed in Chapter Seven) allowing the results to be compared which may allow conclusions to be made about which inflow scenarios were most likely. The impact of the merged scenario is shown clearly in each graph – flow peaks caused by rainstorms in the spring catchment are cut off by the smaller capacity of the channel. The significance of this restriction can be seen most clearly in Figure 5.3, Figure 5.4 and Figure 5.5.

These figures also give an indication of how inflow tends to vary across the year – the first four to five months of the year have high flows and frequent storm peaks, the summer months – May to September – tend to be characterised by a drop in flows for the first months of the summer, although storm peaks remain relatively frequent and the second half of the summer when the number of storm peaks and their intensity is reduced but the base level flow is higher. The remaining months of the year – October to December – tend to have less frequent but more intense storms which leads to flow see-sawing between high and low values. The low flow year has fewer storm peaks (= fewer rainfall events) than the average and high flow years. The graphs also make clear the level of variability that could have been experienced with the parallel system. In the merged system, variability in flow only occurs when flows are particularly low, and as such variability could be used as a trigger for changes in management of the system. For example, any drop in flow could be used as a signal to stop storing water in the large peripheral cisterns in order to pass more water into the city. In the more variable parallel arrangement, a more sophisticated decision mechanism would be required.

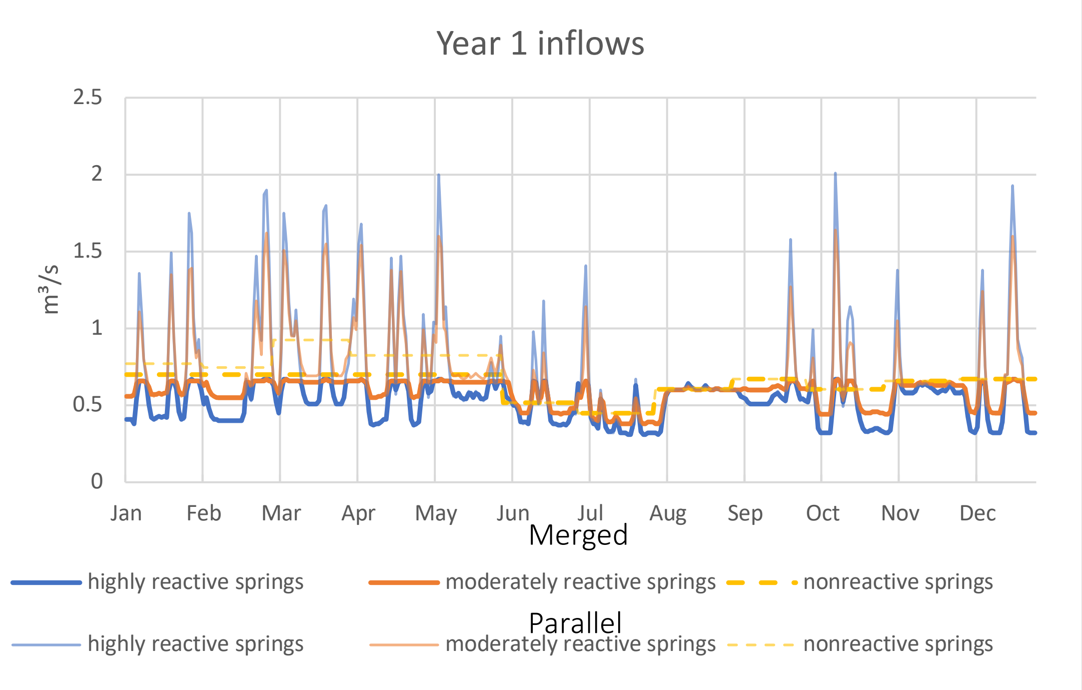


Figure 5.2: Water inflow to the city for Year One (low) rainfall in the merged and parallel scenarios.

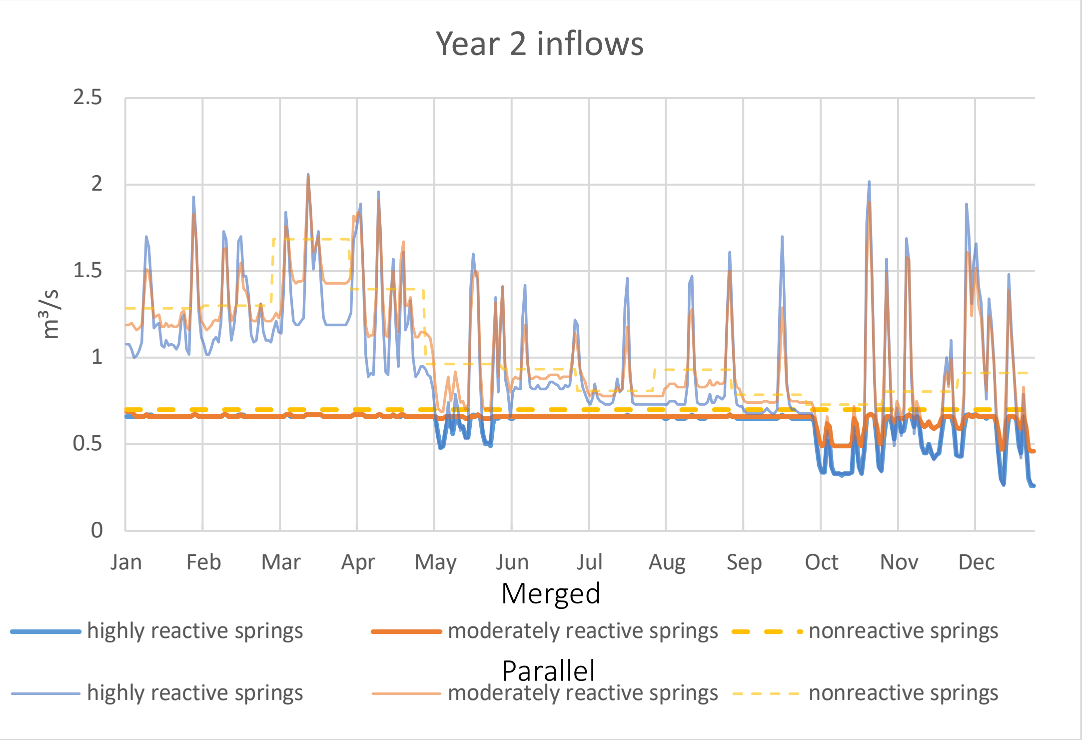


Figure 5.3: Water inflow to the city for Year Two (average) rainfall in the merged and parallel scenarios.

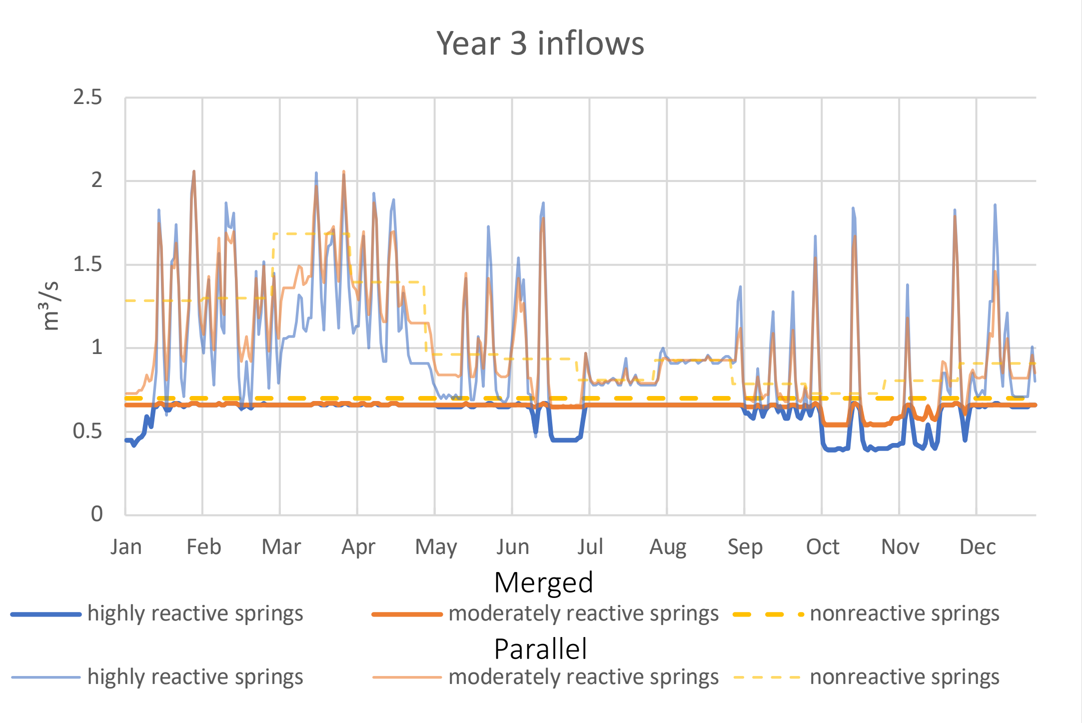


Figure 5.4: Water inflow to the city for Year Three (average) rainfall in the merged and parallel scenarios.

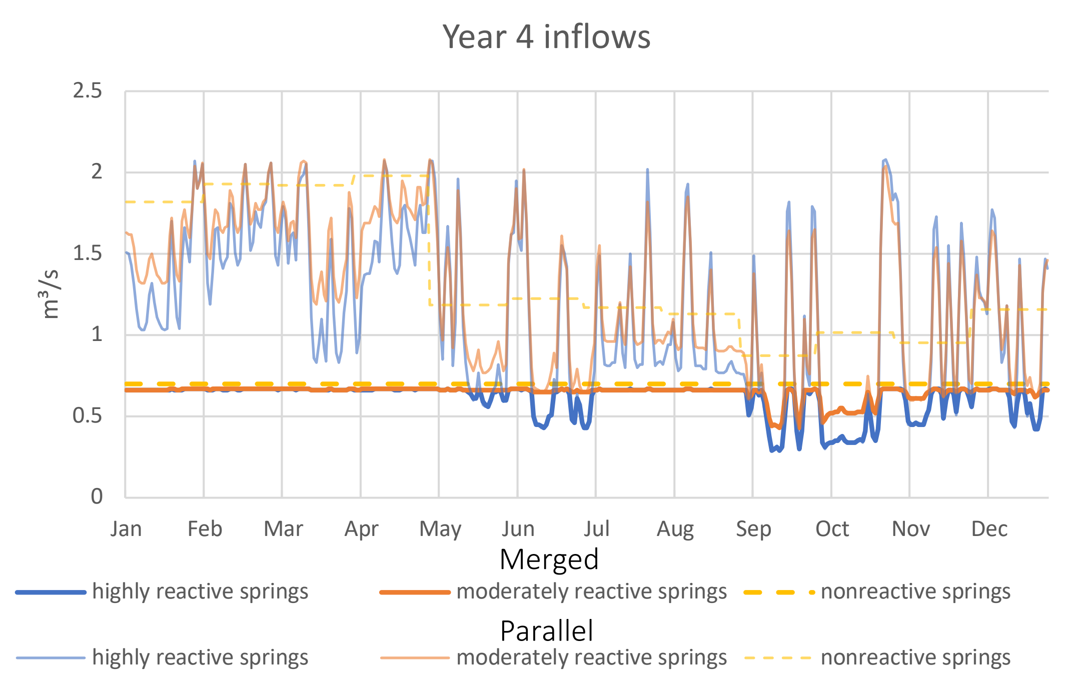


Figure 5.5: Water inflow to the city for Year Four (high) rainfall in the merged and parallel scenarios.

### 5.3.2 Aqueduct of Hadrian

Evidence for the characteristics of the water flow in the Aqueduct of Hadrian is sparse; contemporary information provides two perspectives. A law of the mid-5th century restricts use of this aqueduct to the Great Palace and one (or two) public baths (Cod. Just. 11.42.6 Frier *et al.* 2016). These are all likely to be high water users, so the aqueduct must have been capable of supplying them but perhaps not much more, so needed to be protected from additional offtakes, which might cause failures of service to the baths or the Great Palace. On the other hand, it is believed that the Aqueduct of Hadrian served as the city's primary water source during the years 626-765 (Crow *et al.* 2008, p. 20), from the Avar siege that cut the Aqueduct of Valens till a severe drought prompted its repair:

> *"…water entirely disappeared from the City. Cisterns and baths were put out of commission…"*
>
> (Theophanes Chronicles 6258 (Mango & Scott 1997))

If we assume that there were no temporary fixes to the Aqueduct of Valens[39] bringing water at a high level, then the Aqueduct of Hadrian sustained the city and some of its baths for almost a century and a half. The Aqueduct also sustained the city as the sole supplier of water during its first four decades. Although there is no quantitative data for this period, the evidence from texts suggests that the flow was not insignificant.

For figures, it is necessary to move forward in time and look at the Kırkçeşme system, part of the Ottoman water supply which also took water from the Forest of Belgrad so can serve as a rough proxy for the older system. The Ottomans constructed reservoirs at the head of the system which may have acted to balance and stabilise the flow available. There are four figures for flow given in Table 5.1. These cover the whole period of service of the Kırkçeşme system, from the mid-16th century to the early-20th century. The Ottoman system of measurement was the *lüle*, a more sophisticated development of the Roman

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[39] If the city was reliant only on the Aqueduct of Hadrian, which is at a relatively low elevation, large proportions of the city would be "dry" particularly all the large civic constructions along the Mese – Constantine's column and the surrounding forum, Forum Tauri, the Greater Nympheum, numerous mansions and palaces and almost all the large cisterns.

*quinaria.* A *lüle* was a pipe of diameter 26 mm and installed in a basin with the water level maintained 96 mm above the centre of the pipe, this arrangement produced flow of 36 l/min or 52 $m^3$/day (Çeçen 1996a, p 69-71). These conditions created a consistent flow and allowed allotments of water to be made at distribution chambers and smaller pipes scaled to the *lüle* enabled fractions to be used.

It is not known how flow in Byzantine times related to the Ottoman figures – it seems unlikely to be higher, given that this was the main source of water for the Ottomans and they constructed a number of reservoirs to make the source resilient. Equally, it is unlikely to have been significantly lower than the Ottoman figures given that it served a number of prominent sites and was capable of sustaining the city during the early years of Constantinople. There is also little information about how the water supply would have varied during the year – Sinan notes that the measurement from 1568/9 is for August/September, the period when water levels could be low due to dry summer weather. But it is also worth noting, as Çeçen (1996b, p. 171) does, that this was the period in which the Kırkçeşme system was being reconstructed after devastating floods in 1563 so the low figure might be attributed to the poor functioning of the system as well as the time of year. For the model of the Byzantine system I propose, given the lack of evidence on which to base seasonal or other variation, to initially use the 1715 figure of 9332 $m^3$/day as a flat-rate throughout the year.

Table 5.1: Recorded yields of the Ottoman Kırkçeşme system

| **Date** | **Source** | **$m^3$/ day** | ***lüles* (conversion used in text)** | **Notes** |
|---|---|---|---|---|
| **1568/9** | Sinan (Çeçen,1996b, p. 155) | 884 | 17 (52 $m^3$ = 1 *lüles*) | Dates from the start of Sinan's project to reconstruct the Kırkçeşme system. The very low figure, from the driest part of the year |
| **1715** | Hadizade Efendi (Çeçen,1996b, p. 155) | 9332 | 179 + 3 *masuras* + 3 *çuvaldızes* (52 $m^3$ = 1 *lüles*) | |
| **1810s** | Andreossy 1828, p. 422 | 7330 | 134 (54.7 $m^3$ = 1 *lüles)* | Andreossy converts lüles to pounds and quarts of water. I have converted this to litres (2 pounds = 1 quart, 1 quart =1.14 litres). |
| **1920s** | Dalman 1933, p. 34-5 | 12600 | 210 (60 $m^3$ = 1 *lüles*) | Dalman offers two figures for converting from lüles to $m^3$ (p 20-1) 47.86 $m^3$ and 60 $m^3$ however neither of these tally with Çeçen, who writing in the 1990s had access to more recent work on the Ottoman system of water measurement. Dalman's description of a lüle is also slightly off – the distance from centre of the nozzle to the lip of the basin is taken as 96 mm not 94 mm, and, more critically, the diameter is 26.4 mm not 13 mm. It is also not clear whether the figure given for the yield of the Belgrad Forest is current and whether it was measured in lüles and converted to $m^3$ or vice versa. |

### 5.3.3 Rainwater harvesting

Rainwater was the main source of water for a number of cisterns across the Roman world, as discussed in Section 3.2. Could this also have been the case in Constantinople? It is possible, and likely, that the smallest, domestic cisterns relied on water captured from building roofs and courtyards. However, there is little evidence to support rainwater as the *primary* provider of water to the larger cisterns, although some of the larger cisterns that remain have small inflow pipes intruding through roofs which suggest that they were supplemented by rainwater.[40] For rainwater to be the primary source, the collection areas required for the larger cisterns would be colossal, but the collection area available is restricted by the topography of the city, with steeply sloping spurs and cisterns generally located high up the slope. The tendency for cisterns to be found in clusters also reduces the available collection catchment per cistern. The evidence for rainwater harvesting can be considered with a case study looking at the cisterns on Hill One.

#### Hill One Cisterns

Hill One is a reasonable case to consider for rainwater harvesting as it is separated from the rest of the city by a valley, as shown in Map 5.4 and there is no evidence or record of a bridge or siphon structure bringing water from the Aqueduct of Valens channel on Hill Two (and the Aqueduct of Hadrian is too low to supply the top of the hill). Yet Hill One is one of the most densely populated in terms of cisterns, which must have received water from somewhere. To consider the possibility that Hill One relied entirely on rainwater, we first must identify which cisterns would need to be rain-fed – those that are located above the Aqueduct of Hadrian (see Section 6.3 on the likely route of the aqueduct) which are highlighted in Map 5.4. The maximum catchment is 115,000 $m^2$ shown as the area upslope of the cisterns in Map 5.4.

There are 14 cisterns in this area, seven of unknown volume whilst the other seven have a total volume of 18,850 $m^3$. Rainfall in the Late Antique period varied from 630 mm to 730 mm which is roughly similar to the modern day

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[40] Even the basic calculation in Crow *et al.* (2008, p. 141), which takes no consideration of water use or seasonal variation, concludes that rainwater harvesting was not a realistic prospect for the city.

annual average.[41] The final element to consider is the population reliant on these cisterns for water. Water demand and population distribution is discussed in detail in section 5.4, for now we can use Jacoby's (1961) estimated density of 500 people/ha. The population catchment is determined using Thiessen polygons and is shown as the area in Map 5.4: this area of 367,000 m$^2$ could house a population of 18,350. A high-level calculation based on the upper limit of rainfall (730 mm) shows that there would be 12.5 l/person/day. This amount of water per day is sufficient for survival but below the 20 l/p/d used by WHO as a measure of basic access (WHO n.d.). However, as soon as the calculation is made more realistic – reducing the catchment below 100%, assuming some losses of rainfall and allowing for evaporation and taking into consideration the variation of rainfall across the year and the water needed for the public and private baths around Hill One (see Map 5.2) – the per capita availability becomes unfeasible. Therefore it is concluded that rainwater was not the main source of water on Hill One (or elsewhere) and that the water from the Aqueduct of Valens was the main source for these cisterns.

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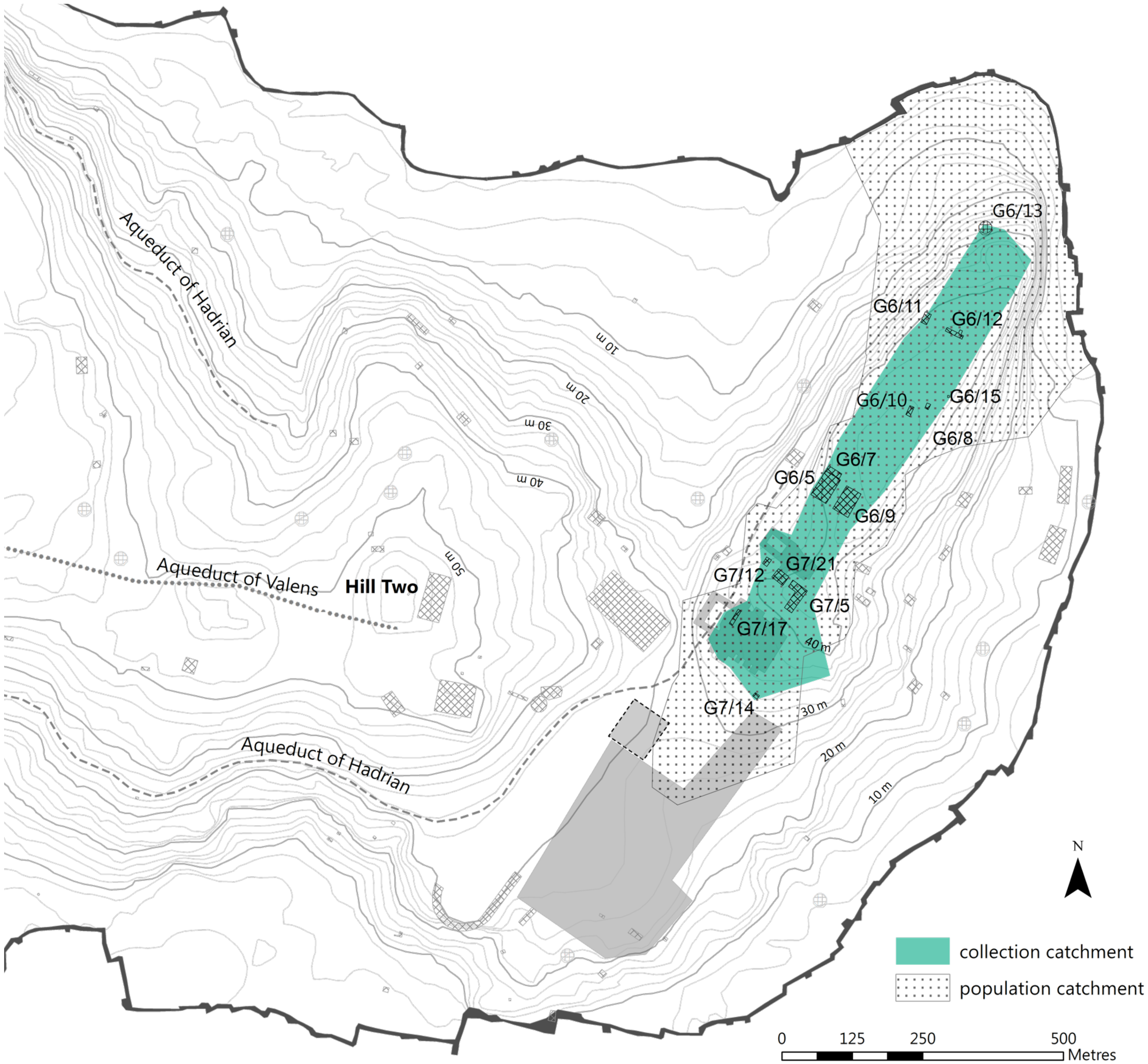
[41] These figures are from a preliminary macrophysical climate model (MCM) kindly carried out by Bülent Arikan on behalf of the project. For a full discussion of the MCM results, see Ruggeri (2018 PhD Thesis).



Map 5.4: The rainwater catchment area available to cisterns on Hill One and the area dependent on those cisterns as the nearest water source.

### 5.3.4 Halkalı springs and the Mokios cistern

The final potential major source for the city are the Halkalı springs which are located 15 km northwest of the city and are at a relatively high elevation (see Map 5.3). These springs were exploited by the Ottoman water system to provide water to the higher areas of the city crossing the Bozdoğan Kemeri to supply, amongst other places, the Topkapı Palace. The yield of the Halkalı springs is reported to be low (Dalman (1933) reports 6000 $m^3$/day and Çeçen (1991) 4212 $m^3$/day), and the Ottoman system constructed to exploit them is elaborate – 16 separate lines convey water from the area of the springs into the city (Çeçen 1991, p 30). The low yield perhaps explains why the Byzantines did not use it as a main source for the Aqueduct of Valens even though it is at a high enough elevation to supply the highest parts of the city and is substantially closer than the springs that were used. However, it is possible that the springs were exploited to feed a smaller catchment – Hill Seven (the dry hill) – which was furnished with water when Mokios – the largest of Constantinople's cisterns – was constructed in the late fifth or early sixth century. Even with Dalman's higher figure for yield, the springs would take nine weeks to fill but once full, the enormous open-air cistern would be a significant resource for this area of the city.

If the Halkalı springs did not supply the water to Mokios, the other viable alternative would have been a branch line from the Aqueduct of Valens. To reach the cistern the branch line would have to cross the Lycus valley, either separating some way outside the city (although any new line, whether from Halkalı or a branch from the Aqueduct of Valens, would need to cross through the Theodosian Walls which would have been a significant challenge) or branching from within the city walls and crossing the valley by siphon. Using the Aqueduct of Valens to feed Mokios would have widened the area with access to water but, as a result, reduced the quantity reaching the heart of the city.

## 5.4 Water Demand

On a street in Constantinople, a man carries a vessel to a fountain, collecting water for his home. On the return journey he passes a fuller, rinsing cloth in a series of basins; then a potter using water to shape clay in his workshop; the oxen that have delivered fuel to the nearby forge are being watered at a trough; from a bakery, dirty water is flushed out into the street drain; fountains splash in an elite house with its own piped water supply, and on the other side of the road a small private bath complex offers a place to wash closer to home than the lavish public *thermae*.

⁂

Demand for water was everywhere in Constantinople, with all the commerce, industry and imperial functions that a huge population creates. Although such a picture can be painted for Constantinople, or any sizeable city of the period, relatively little is known about the precise detail of how the city used its water.

There are three key questions when considering water demand: who or what is using water, where is it being extracted from the system, and how much is being used? Although for Constantinople none of these questions can be answered definitively, the available evidence has been pieced together to create an estimate for water demand across the city and allow the system to be considered as a working whole. Data available on different uses is not precise enough to allow it to be used as the basis of a model so a different method of representing water demand must be found. There is not a continuity of water use over time, so it is not feasible to adapt a modern water demand assessment for the city: expectations of access were different; some water uses prominent then, such as watering animals used for transport, no longer exist; and others, such as domestic use, were much lower than modern standards. The simplest model of water demand would be a uniform distribution across the city. However, through consolidating what we know, though incomplete, regarding the three key questions, we can generate a more refined model of water demand.

### 5.4.1 How was water used in Constantinople?

For Rome, Frontinus listed various water users including public baths, (military) camps, fountains and water basins, (other) baths, public structures, private parties, houses and fullers (Front. 78-86, 91). Broadly there are three separate areas of water demand: domestic, commercial and civic.

There are some key major water users in the city: the large public baths are likely to have been the most significant individual water users in the city – in Rome, construction of the Baths of Caracalla required a new aqueduct branch and large holding cisterns (DeLaine 1997, p. 16); in Carthage the Antonine Baths drew water from the dedicated 20,000 m$^3$ Bordj Djedid cistern (Wilson 1998).

Figure 5.6: The remains of the *nymphaeum* at Gerasa (now Jerash, Jordan) indicate the grandeur and spectacle associated with nymphaea. (Photo credit: Jordan Klein from San Francisco, United States (Flickr) [CC BY 2.0 (http://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons)

The sprawling Great Palace with fountains, water displays and baths would have been a significant water user and had its water supply protected in law. Some civic structures would have required a regular water supply, such as the Hippodrome, which, with regular races and a capacity of 100,000, would need water to support both horses and spectators; others such as the nymphaea (combinations of statues, many fountain spouts and large pools, for example the ruins of the nymphaeum in Gerasa, shown in Figure 5.6, which still evoke the grandeur of the original), did not so much need water as provide it, although their spectacular displays might have led to a higher proportion of water flowing into the drainage system than a basic water spout and basin.

Although not all commercial premises would have been major water users, there were many thousands of them across the city, so commercial water use as a whole would have been significant. Commercial water use would include textile production, dyeing and washing services (laundry in the Roman period was carried out by a fuller), metal and ceramic work, and food production. Bread-making would have required water in the dough and also for general cleaning, as would butchers and other food processors. Commercial water use should also take into consideration the need for water in the transport network. At a time when everything on land was moved by animal (or human) power, it is important to take account of the need to keep pack and draft animals fed and watered.

Domestic water use would have been considerable in the city, even if most individual consumption was low. Domestic water use was split into two extremes: the majority of the population would have relied on collecting water from public fountains and carrying it home. This method of water supply naturally puts a limit on how much water is used. These households were unlikely to make “frivolous” use of water, collecting and carrying only what was necessary – sufficient water for drinking, cooking and some cleaning. Many of the large water use tasks in the modern household – toilets, washing clothes and washing the body – would have occurred outside the home in Byzantine times. At the opposite end of the water use scale are the elite households that had access to piped water. The potential quantities of water delivered in a piped system, discussed in the next section, are large. What was the extra water used for? From the law codes, it is clear that one use would have been in household baths: having baths warranted at least a 1.5 inch diameter pipe though there was a smaller pipe size available for households without baths (*Cod. Theo.* 15.2.3, trans. Pharr 1969). In Pompeii, houses connected to the piped water supply often used the pressurised system to power household fountains and water displays (Jansen 2001).

Given the large population, food production would have been a concern for the city. Constantinople relied on Egyptian wheat imports until the loss of Egypt from the Byzantine Empire in the early-7th century. There is evidence that other foodstuffs were also imported (wine, olives, legumes, bacon and grain were all subject to import tax) however perishable food, including salad, vegetables and fruits would need to be grown either close to or within the city. Koder (1995) considers the evidence of a chapter of the *Geoponika* that discusses the vegetables grown in Constantinople and probably dates to the early 6th century. There was, therefore, at least some agriculture in Constantinople, probably concentrated in the sparsely populated area between the Constantinian and Theodosian Walls, and this was likely to have had some requirements for water in order to irrigate crops. The climate in Constantinople was not typically Mediterranean, tending to have colder periods during the winter months, so year-round agriculture may not have been feasible but irrigation would have been necessary for large scale food production in the hotter months.

Other significant water users include monasteries, hospitals and harbours. For monasteries and other religious institutions, water use probably reflected typical domestic use perhaps with additional water for irrigation – the monastery of St Olympias was allowed a 3-inch diameter pipe water supply (*Translatio Olympiadis* quoted in Crow, Bardill & Bayliss 2008, p. 233). A hospital was positioned between Hagia Sophia and Hagia Eirene, the quantity of water likely to be used in a Byzantine hospital is unknown, although it is perhaps telling that the position on Hill One was in close proximity to several large cisterns. The harbours are likely to have required a good supply of water perhaps for industrial uses (such as ship construction and repair) and, as a minimum, to provision departing ships.

### 5.4.2 Where were water users were located?

For a city-scale model it is important to establish a distribution of demand across the city as it will enable detailed consideration of cistern use and overall water management. The *Notitia Urbis* is the main source for locating baths, industry and the population within the city, but this only provides a high-level regional scale distribution for the early 5th century. Knowing where a large public bath is located within a region is difficult although taking into account the proximity of the water supply and the steepness of the topography can narrow the options. Smaller-scale water users are more difficult. The *Notitia Urbis* describes Region V as containing “the buildings that supply the city with its necessities” as it contains the Strategion (an important market area), both naval and commercial harbours, and imperial warehouses (Matthews 2012). It is likely that there may have been a similar concentration of commercial and industrial activity around the harbours on the southern side of the city in Regions III, IX and XII. But there are also indications of non-domestic users throughout the city. *Stoai*, the porticoes that would have housed shops, workshops and other commercial premises are noted in every region of the *Notitia Urbis*. Mundell Mango (2000) estimates the *stoai* listed in the *Notitia Urbis* could have housed at least 2,600 shops, and notes that the Church in Constantinople had 1,100 shops that it drew income from (Mango 1985, p. 48). Given that commercial premises were not limited to *stoai*, there must have been many thousands across the city. Not all shops required water supply but excavation of the shops at Sardis shows that many had either flowing water or provision for water storage (Stephens Crawford 1990).

Mundell Mango (2000) draws together the evidence on commercial premises in Constantinople. For the early period, spatial evidence is scant: book-copiers and sellers are near the Augustaion (located between the Hippodrome and the Hagia Sophia), coppersmiths are known in the area to the north of this; silversmiths and furriers are linked to the area of the Mese between the Milyon and Forum of Constantine (Mundell Mango 2000, p. 197 and plate 20). There is little other evidence – some *stoai* had a mixture of different commercial premises rather than a grouping of the same trade, and the combination of harbours, warehouses and markets listed in the *Notitia Urbis* indicate that Regions V, VIII and IX were of particular importance to food production and business (Mundell Mango 2000, p. 197-8). For a bustling metropolis, this is not a lot to go on, but a lack of particulars does not indicate that there was no demand for water. The knowledge that commercial premises existed outwith the *stoai* and that there were many thousands of them across the city strengthens the argument that with some exceptions (such as those whose trade was required to be kept separate, like cheesemakers) in general, the distribution of water users follows that of the general population.

### 5.4.3 How much water was used?

The amount of water used by processes in the Roman and Byzantine period has not been studied in any detail, which makes developing a comprehensive water demand model challenging. This section outlines what can be deduced about the various water uses identified above but ultimately concludes that there is insufficient data to create a water demand model with any level of detail or precision that reflects the complex reality.

#### Public baths

Public baths, with functions beyond mere hygiene, could be lavish users of water, attested by Seneca's description of a display in baths with "masses of water that fall crashing from level to level" (Seneca, Letters 86.7). The baths or *thermae* were large civic spaces where the population could go to socialise, exercise and bathe. Typically, bathers would start with the *tepidarium,* a heated area supplied with warm water; then the *caldarium*, a hot room with basins of cold water to relieve the bather and possibly hot water pools as well; a *suditorium,* a hot steamy room might be present; and the final stage was a plunge into the cold pool of water in the *frigidarium*. A *natatio*, or swimming pool, would also be present in the largest baths. In addition, baths would have toilet facilities (that might have been flushed with waste water from the bathing areas), showers, and visual displays of water in fountains and pools.

How much water did the *thermae* use in order to provide this luxurious service to the public? For the Baths of Caracalla, it is estimated that the still water pools could hold 2000 $m^3$ with the *natatio* alone holding 1400 $m^3$, whereas in Ostia the capacity of the *caldarium* was a mere 1.5 $m^3$ (Yegül 1992, p. 394). The smaller size was probably because it was dependent on a man-powered waterwheel only capable of lifting 1 $m^3$/hr, which would clearly discourage profligate use of water (Yegül 1992, p. 390-395, 2010, p. 97-100). The Caracalla figure excludes water for showers and fountains and it should be clear that the total storage volume of pools does not equate to daily water use – for example the Thermae of Agrippa in Rome are estimated to have received 19000 m$^3$ of water per day (Shipley 1933 cited in Yegül 1992, p. 394).[42]

Baths were used by thousands every day and may have been open from dawn till sunset in order to accommodate separate bathing for men and women where separate facilities were not available (Yegül 2010, p. 33). This suggests that to keep the water clean and at the appropriate temperature, there must have been a substantial flow of water throughout the day. Wilson (1998) speculates water use of 4000 m$^3$ a day for the Antonine Baths in Carthage based on estimated inflows from the aqueduct and storage capacity of the Bordj Djedid cistern. 4000 m$^3$ a day seems a reasonable initial assumption for the public baths in Constantinople, a significant but not stupendous figure that ties in with the inflow from the Aqueduct of Hadrian (9332 m$^3$/day) being capable of feeding the Zeuxippos Baths, the Achilles Baths, the Great Palace and not much else.

### Private baths

There were two smaller levels of bath, the neighbourhood *balnae* which is probably the private bath listed in the *Notitia Urbis* and domestic baths in the houses of the elite. The minimum size of pipe offered to houses with baths was 1.5 inch (for "houses of mediocre or inferior merit" with baths (Cod. Theo. 15.2.3 trans. Pharr 1969), which could reasonably deliver 40-100 m$^3$/day depending on the pipe length and head (see Table 5.2). For both *balnae* and private household baths, water use is likely to have been significantly lower than the public baths, with only smaller basins of water and a couple of rooms kept at different temperatures. Given the access to piped water, an estimate of 5-10 m$^3$/day seems reasonable.

### Domestic collection

The most obvious factor constraining those who had to collect water from public fountains would have been weight. Carrying 10-20 kg of water (plus the weight of the container) any great distance is a significant burden. For the majority of

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[42] However, Shipley (1933 p. 53-54) seems to indicate that the 19,000 m$^3$ was for the Euripius, an artificial waterway that was adjacent to the Agrippa Baths, rather than for the baths themselves.

households, domestic water use would be low, probably between the 7.5 to 15 litres/head/day that represents the modern minimum standard for survival (SPHERE n.d.). The majority of a typical person's water use would occur outside the home.

### Domestic piped

A small number of users would have been able to pay for (or obtain by other means, as suggested by the wording of several laws about water misuse discussed in Chapter 2) a private piped water supply. There are a number of factors that determine how much water could potentially be delivered through the piped systems which varied in diameter from 0.5 to 3 inches. If the pipe runs under pressure,[43] the determining factors include pipe diameter and length, the roughness of the pipe material (large diameter stone pipes and smaller ceramic pipes have been found) and the head of water pushing through the pipe. Table 5.2 indicates the calculated volume delivered in 24 hours for each pipe size for a range of head, pipe length and pipe roughness. The flow values in Table 5.2 were obtained by comparing calculated headloss values with the assumed available head. Headloss was calculated using the Darcy-Weisbach equation (eq 5.1) and the (lambda) value calculated by applying the Colebrook-White transition formula, either by the Moody equation (eq 5.2) or the Barr equation (eq 5.3) depending on the Reynolds number. A nominal allowance for minor headlosses, of $2.5 \times {V^2}/{2g}$ was also included.

$$H_f = \frac{\lambda L V^2}{2gD} \qquad \text{(eq 5.1)}$$

$$\lambda = 0.0055\left[1 + \left(\frac{2000k_s}{D} + \frac{10^6}{Re}\right)^{1/3}\right] \qquad \text{(eq 5.2)}$$

---

[43] Potentially the piped systems could have operated as open channel flow. Ortloff (2009) investigates the consequences of pipes in Ephesus that may have run as open-channel or pipe-full flow. There are potential challenges if the flow regime within the pipe can flip back and forth between open-channel and pipe-full. For this study, it is considered that flow would have been pipe-full and that the outflow at the house was controlled by a tap or submerged flow into a holding tank.

$$\lambda = \left( \frac{1}{-2\log\left(\frac{k_S}{3.7D} + \frac{5.1286}{Re^{0.89}}\right)} \right)^2 \qquad \text{(eq 5.3)}$$

Domestic supply pipes are assumed to be ceramic with the roughness likely similar to those used by Haut & Viviers (2007) who used values between 0 mm and 0.5 mm to represent glazed pipes (lower end of the scale) and pipes with a calcareous deposit (upper end). Pipe length and head could vary widely, but investigating combinations of pipe length between 10 and 200 m and head between 1 and 10 m shows that the smallest pipe, the 0.5-inch diameter, could deliver between 3 and 6.6 litres minute (the typical delivery rate of a modern tap is about 12 l/min). In contrast, the largest pipe would be capable of delivering between 135 and 735 litres/minute. This is the maximum potential capacity of the pipe over 24 hours, rather than a suggestion that this was the amount of water actually used by the household.

Clearly the potential maximum water consumption in a domestic setting is huge. However, there is no indication that those with a private supply left it constantly running. Indeed, it is possible to infer that they did not – otherwise a relatively small number of piped connections would overwhelm the available water. Only those of the highest rank would have been entitled and able to pay for the larger pipe sizes but the number of houses that were connected to a piped supply in Constantinople is not known. About 10% of houses in Pompeii were connected to piped water, but following this line of thought again leads to the difficulties of interpreting the word *domus* in the *Notitia Urbis* and raises questions about the appropriateness of using a figure from a 1st century small city for a 6th century major one. For example, in Pompeii, piped water was primarily used for fountains but in Constantinople, there appears to be specific provision for baths. 10% of the population would equate to roughly 3600 households (assuming population of 360,000 and 10 people per household). If we use the worst 1.5-inch pipe capacity scenario in Table 5.2 as an average for all users, private water use could account for up to 79,000 m$^3$/day, which is tremendously high and not possible based on the inflow figures assumed.

Table 5.2: Range of maximum volume delivered in 24 hours (m$^3$/day) in 3, 2, 1.5 and 0.5 inch pipes for a range of pipe length (m), head (m) and roughness (mm) (see p. 145-6 for explanation of calculation method). Figures in grey are considered unlikely due to the extreme gradients (1 in 5 or steeper).

3 inch

0.03 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | 216 | 324 | 454 | 583 | 778 |
| | 2 | 324 | 454 | 626 | 821 | 1102 |
| | 5 | 540 | 734 | 1015 | 1339 | 1771 |
| | 10 | 756 | 1058 | 1447 | 1901 | 2527 |

0.06 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | 216 | 302 | 432 | 583 | 756 |
| | 2 | 324 | 454 | 648 | 799 | 1080 |
| | 5 | 540 | 691 | 972 | 1274 | 1706 |
| | 10 | 713 | 1015 | 1382 | 1836 | 2441 |

0.1 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | 216 | 302 | 432 | 583 | 734 |
| | 2 | 324 | 454 | 583 | 778 | 1037 |
| | 5 | 540 | 670 | 929 | 1231 | 1663 |
| | 10 | 691 | 972 | 1318 | 1771 | 2376 |

0.5 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | 194 | 302 | 410 | 562 | 648 |
| | 2 | 302 | 432 | 583 | 648 | 929 |
| | 5 | 497 | 583 | 778 | 1058 | 1469 |
| | 10 | 648 | 799 | 1102 | 1490 | 2095 |

2 inch

0.03 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | 65 | 108 | 151 | 216 | 302 |
| | 2 | 108 | 151 | 216 | 302 | 410 |
| | 5 | 173 | 259 | 367 | 475 | 670 |
| | 10 | 259 | 389 | 518 | 691 | 972 |

0.06 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | 65 | 108 | 151 | 216 | 302 |
| | 2 | 108 | 151 | 216 | 302 | 410 |
| | 5 | 173 | 259 | 367 | 454 | 648 |
| | 10 | 259 | 389 | 475 | 670 | 929 |

0.1 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | 65 | 108 | 151 | 216 | 302 |
| | 2 | 108 | 151 | 216 | 302 | 389 |
| | 5 | 173 | 259 | 367 | 432 | 626 |
| | 10 | 259 | 389 | 454 | 626 | 907 |

0.5 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | 65 | 86 | 130 | 194 | 281 |
| | 2 | 86 | 151 | 194 | 281 | 389 |
| | 5 | 173 | 238 | 346 | 410 | 540 |
| | 10 | 238 | 346 | 389 | 518 | 756 |

Table 5.2 continued

1.5 inch

0.03 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | 22 | 43 | 65 | 86 | 151 |
| | 2 | 43 | 65 | 108 | 151 | 216 |
| | 5 | 86 | 108 | 173 | 238 | 324 |
| | 10 | 108 | 173 | 259 | 324 | 475 |

0.06 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | 22 | 43 | 65 | 86 | 151 |
| | 2 | 43 | 65 | 108 | 151 | 216 |
| | 5 | 65 | 108 | 173 | 238 | 324 |
| | 10 | 108 | 173 | 259 | 302 | 454 |

0.1 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | 22 | 43 | 65 | 86 | 151 |
| | 2 | 43 | 65 | 86 | 151 | 216 |
| | 5 | 65 | 108 | 173 | 238 | 302 |
| | 10 | 108 | 151 | 259 | 302 | 432 |

0.5 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | 22 | 43 | 65 | 86 | 130 |
| | 2 | 43 | 65 | 86 | 130 | 194 |
| | 5 | 65 | 108 | 151 | 216 | 259 |
| | 10 | 108 | 151 | 216 | 281 | 367 |

0.5 inch

0.03 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | - | - | - | 5.2 | 8.6 |
| | 2 | - | - | 5.2 | 7.8 | 13.0 |
| | 5 | 4.3 | 6.0 | 9.5 | 13.8 | 22.5 |
| | 10 | 6.5 | 8.6 | 13.0 | 17.3 | 30.2 |

0.06 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | - | - | - | 5.2 | 8.6 |
| | 2 | - | - | 5.2 | 7.8 | 13.0 |
| | 5 | 4.3 | 6.0 | 9.5 | 13.8 | 22.5 |
| | 10 | 6.5 | 8.6 | 13.0 | 17.3 | 30.2 |

0.1 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | - | - | - | 5.2 | 8.6 |
| | 2 | - | - | 5.2 | 7.8 | 13.0 |
| | 5 | - | 6.0 | 8.6 | 13.8 | 21.6 |
| | 10 | 6.0 | 8.6 | 13.0 | 19.9 | 32.0 |

0.5 mm (roughness)

| | length (m) | 200 | 100 | 50 | 25 | 10 |
|---|---|---|---|---|---|---|
| head (m) | 1 | - | - | - | 5.2 | 7.8 |
| | 2 | - | - | 5.2 | 6.0 | 13.0 |
| | 5 | - | 5.2 | 8.6 | 12.1 | 19.9 |
| | 10 | 6.0 | 8.6 | 12.1 | 18.1 | 28.5 |

The water used by the piped connections was therefore some value less than those shown in Table 5.2. Whether the restriction on water use was enforced externally (perhaps being only available between certain hours) or was controlled by sensible individual use is not clear. The advantage of having a 3-inch pipe over a 2 or 1.5-inch pipe might have been the rate at which water could be obtained rather than being able to access a larger volume. Alternatively, the number of houses receiving piped water may have been very small, although the fact that there was a law setting out the allowable pipe diameters and the grounds for each suggests a reasonable level of use. This section demonstrates that piped supply could have used huge volumes of water but concludes that in reality water use was much lower than the potential, without being able to specify what that lower value was.

### Great Palace

Water use in the Great Palace, which contained baths, fountains and water displays would have been significant. However, the head available to drive water through a pipe would have been relatively low for certain parts of the palace: the line of the Aqueduct of Hadrian is only a few metres above the northwest edge of the palace (see section 6.3 for full discussion of the route and level of this aqueduct) and about 200 m away from the proposed line of the channel. An open channel may have conveyed the water closer (crossing or navigating around the Hippodrome and Zeuxippos Baths) but this would reduce the head available to power fountains. This is a similar situation to the domestic piped supply discussed above, water use was potentially enormous, but the reality was likely more tempered. As a starting point, I have taken a figure of 100 l/min (6 $m^3$/hr or 144 $m^3$/day) but in order to represent the likely higher burden of the Palace, it is assumed that this use is constant throughout the day (unlike the piped domestic supply).

### Commercial

The information on how many commercial premises needed water and how much they used is too incomplete to form any reasonable estimate of water use. For bakeries, a Roman bread recipe reconstructed from a carbonised loaf preserved in Pompeii, uses just over half a litre of water per loaf (British Museum 2013). Scaled up to a population of 360,000 (see below), this starts to become a non-trivial amount of water. The *fullonica* (laundry) has been found in a range of sizes: from the small single basin arrangement with a capacity of 0.75 $m^3$ in Pompeii, to multiple basin arrangements (also in Pompeii) with capacities around 10 $m^3$, up to the large example in Ostia which has a capacity of over 45

$m^3$ spread across several basins (Flohr, 2013, p. 132-42). Many of the basins were equipped with overflow pipes which may have allowed clean water to be continually added. Whether this means that each *fullonica* used several times its basin capacity every working day is unclear, nevertheless the capacity of basins within each establishment make the *fullonica* a high water user within the city. However, for all other commercial activities, there is insufficient detailed evidence to construct water use estimates.

### Agriculture

The calculation of modern surface irrigation water requirements is complex and given the scarcity of definite information, such a method is not worth pursuing here. To consider irrigation use at a basic level, a figure of 3 mm/day/$m^2$ of farmed land[44] can be used. If this is applied to Koder's (1995) estimate of 300 ha of farmed land within the city walls,[45] the city would require ~9000 $m^3$ per day, a substantial amount, even if it was only necessary in the hotter months of the year.

The sum of the water uses quantified within this section (8 public baths, 153 private baths, 300 ha agriculture, 359,000 people collecting water, 1000 people piped water, taking no consideration of commercial or civic water use) is about 55-60,000 $m^3$/day which is compatible with the inflows of the Aqueduct of Valens in the parallel channel scenario and roughly equal to the peak inflow of the merged scenario. It is clear that there is insufficient data to attempt to assemble a comprehensive model of water demand for Constantinople. It is possible to identify the likely water users, but locating them within the city and quantifying the rate of water use is unworkable. The commercial and industrial uses of water are particularly unquantifiable with the present data. As an alternative to this comprehensive water use model, it is proposed that the focus is placed on

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[44] From the 2005 version of SPHERE guidelines Chapter 2 Appendix 2. However, no guidance on irrigation has been included in the most current version of the guidelines.

[45] Koder's figure of 300 ha should be used with caution as it is a very basic assumption made within an article that focuses on the text of the *Geoponika* rather than establishing likely areas under cultivation. However, as it is the only article that considers agriculture cultivation areas for Constantinople, it will serve as a starting point.

the general population, about which estimated totals have been published and potential distributions can be generated using proxy data.

### 5.4.4 Population – estimation and distribution

The total population of Constantinople has never been conclusively established and there is little, and sometimes conflicting, information to direct the distribution of the population. Although the actual figures are uncertain, it is generally accepted that the city went through an initial period of growth in the 4th and 5th centuries followed by a rapid plague-induced decline in the mid-6th century, then a more gradual recovery in the following centuries, followed by a serious decline after the Latin conquest in 1204. At the time of the Ottoman conquest in the mid-15th century, the population had dwindled to 40-50,000 (Jacoby 1961).

Regarding the distribution of population, Regions I and II are frequently depicted (for example in Tayfun Öner's Byzantium 1200 digital reconstruction of the city) as low density housing areas with the Great Palace and other elite houses surrounded by trees and greenery. In opposition to this, Jacoby (1961) suggests that these areas, being the heart of the old city and continuously occupied since the time of Byzantium, are likely to be among the most densely populated. The number of amenities listed for Region I (and illustrated in Map 5.2) is more supportive of Jacoby's assertion. The growth of the city outward from the heart of the old city is clearly illustrated by emperors' fora and monuments, which appear along the route of the main roads, and increasingly distant from the Hagia Sophia. On the periphery there is the expansion of the city in the 5th century with the construction of the Theodosian Walls and the abandonment of the Constantinian Wall, however it is accepted that this area between the two walls was never more than sparsely populated (Mango 1985, p.48; Jacoby 1961).

Mango (1985) estimates a population of 300,000 to 400,000 in the period of Theodosius II (mid-5th century). Teall (1959, p. 92 and Appendix A) argues there was rapid population growth until 400, caused by immigration leading to a population of about 500,000, followed by stagnation in the next two centuries. On the other hand, Jacoby (1961) suggests a more even period of growth, rising from 90,000 under Emperor Constantine to 375,000 in the mid sixth century. Durliat (1990, p. 256) suggests a population of 600,000 in the sixth century before the impact of the plague. Although the water supply model may eventually be a tool to help critically examine these estimates, currently I am not in a position to assess which estimate is more likely than the others. For the purposes of the model Jacoby's figures will be used.

### The Jacoby model of population distribution

In his consideration of the population of Constantinople, Jacoby (1961) concludes that previous attempts to estimate the population are biased towards the belief that the city had a very large population. He is critical of basing a population estimate on the available proxy data – wheat imports and topographical data from the *Notitia Urbis* – as it requires too many assumptions about wheat density, milling efficiency and variable consumption rates, and questions of interpretation of terms such as *domus*. His preferred model uses population densities, based on the densities seen in medieval settlements. The population model he proposes for Constantinople is split into three areas: the old city, the Constantinian expansion, and the Theodosian expansion; and considers three time periods: the end of the reign of Constantine (mid-4th century), the end of the reign of Theodosius II (early 5th century), and the mid-6th century before the first waves of the Justianic plague.

Figure 5.7 illustrates how the population changes across the three sectors in the Jacoby model. Under Constantine the population is 80,000 and confined to the first two sectors with respective densities of 150 and 100 p/ha. At the end of the reign of Theodosius II, the population rises to 178,000 with densities of 250, 200 and 40 p/ha. By the mid-6th century, the population has risen to 360,000 and

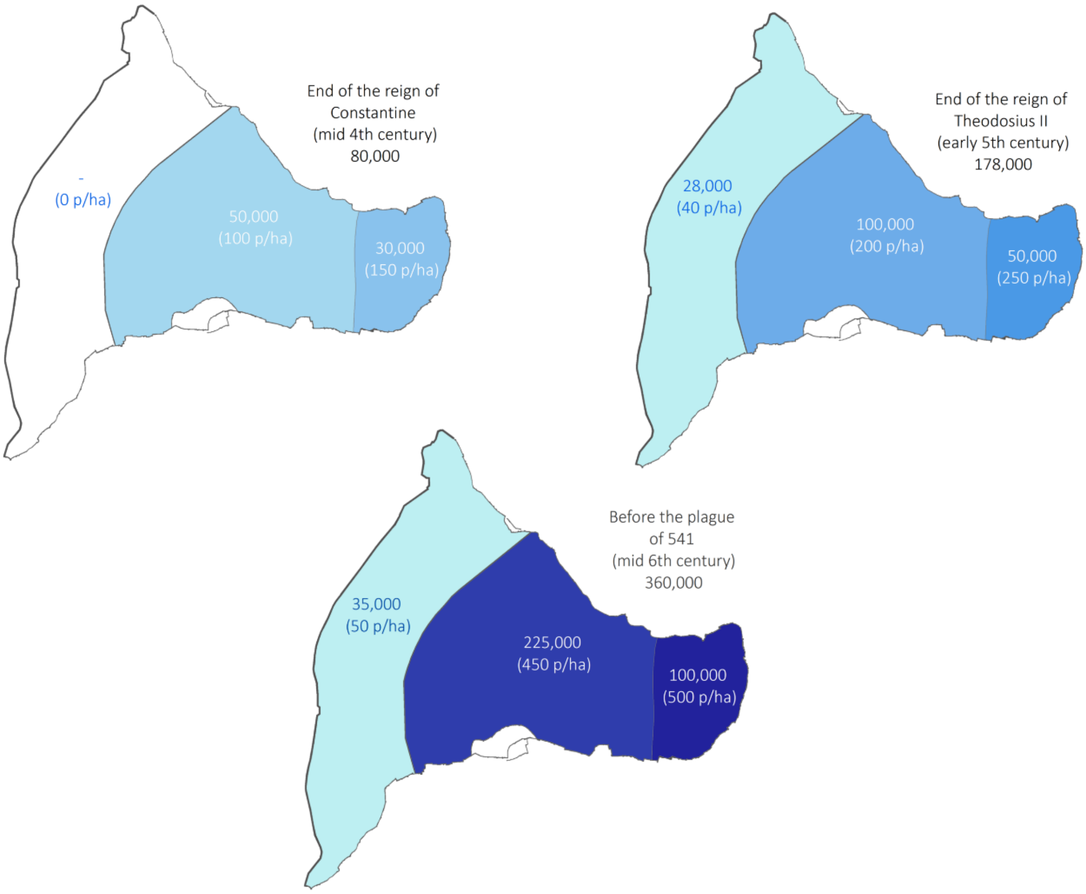
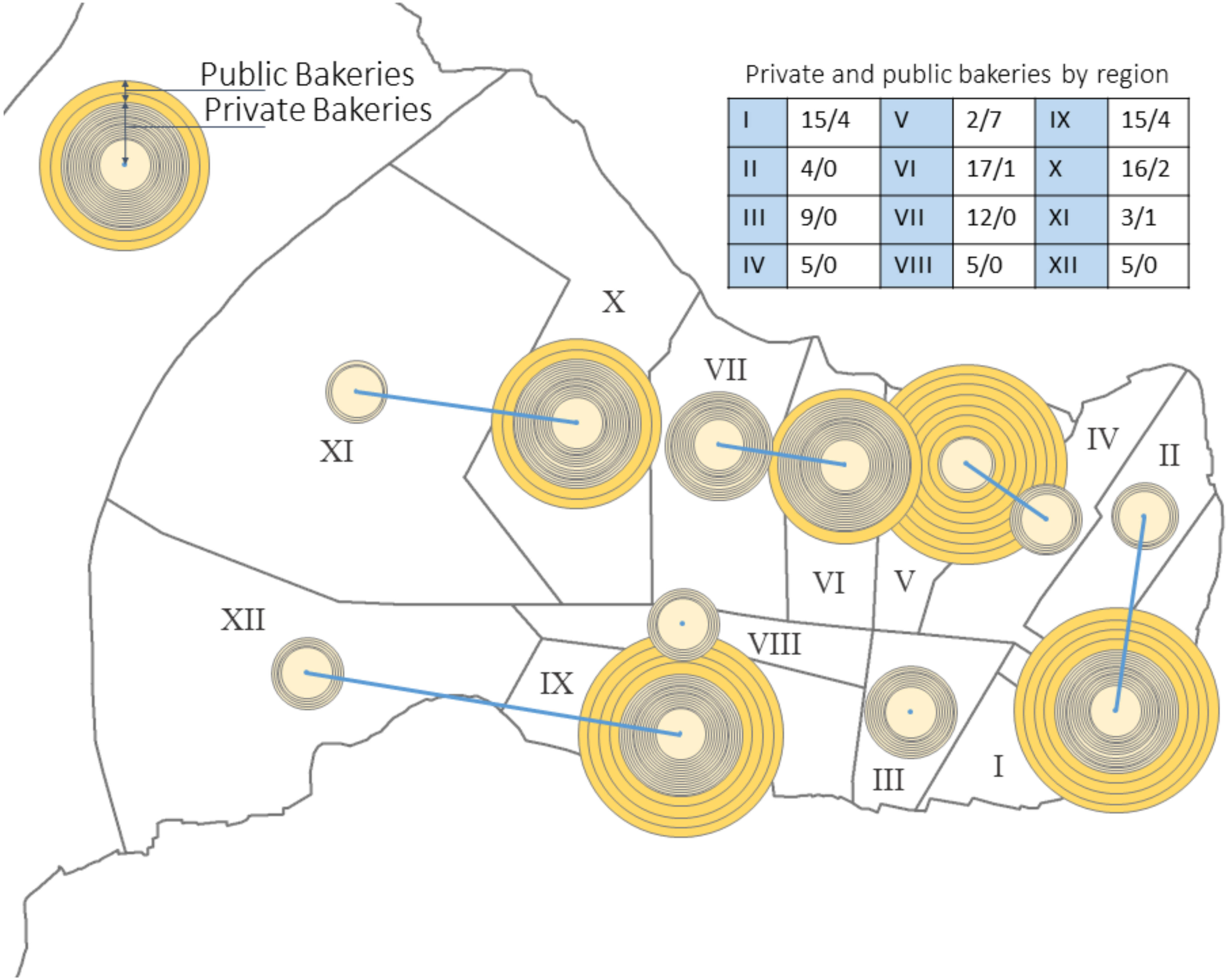


Figure 5.7: Visualisation of Jacoby (1961) population model of Constantinople in the 4th, 5th and 6th centuries. (Values for Sykae (Galata) and Blachernae not included).

densities of 500, 450 and 50 p/ha across the sectors (and a further 15,000 in the areas of Sykae (Galata) and Blachernae which are outwith the city walls and therefore excluded from consideration in the water supply model). The mid-6th century is the particular focus for this project as it corresponds to the point when most of the large cistern infrastructure had been completed and is a time of peak population. The population figure for the Theodosian period is useful for consideration of the population distribution because it is contemporary with the *Notitia Urbis.*

### The bakery as a proxy for population density

In addition to large, singular structures, the *Notitia Urbis* has details of amenities central to everyday life that are present in every region, including bakeries, baths and *gradūs* (the locations from which the *annona*, or free bread, was distributed). The importance of these amenities in considering population distribution is that because they are central to everyday life, their distribution is likely to reflect the distribution of the population. Considering baths, it becomes apparent that the numbers are awkward to interpret – were the private baths listed in the *Notitia Urbis* privately run but publically available (that is, a business providing a service, an arrangement discussed by Mundell Mango (2015)) or part of a private residence and available only to the residents (as perhaps suggested in the Theodosian law code detailing the provision of piped water to private dwellings)? Additionally, we know from Rome that the public baths were large and sometimes extraordinarily large. The larger baths are likely to have had a large sphere of influence – people would have been willing to travel for some distance to use them, so using baths as a proxy could distort the population distribution. The *gradūs* appear in every region but although the *annona* was widespread (Constantine is reported to have supplied bread to 80,000) it was a sign of imperial favour rather than a universal benefit. As such the *gradūs* cannot be assumed to be spread evenly across the population and is an imperfect proxy for population distribution. Although only some citizens received bread for free, it was the staple food of Constantinople, making the bakeries, whether they produced the state-given bread or sold it to private citizens, central to everyday life. There remain some questions regarding the difference between public bakeries and private bakeries and also the role of the bread market (Mundell Mango 2000, p. 201). In spite of these questions, the bakery would seem to be a more appropriate proxy for population distribution. Like baths, bakeries in the *Notitia Urbis* are split into public and private, although no definition of the differences is supplied. For the purposes of this analysis it is assumed that public bakeries, like public baths, are larger than their private counterparts (an arbitrary value of one public bakery being the equivalent of four private bakeries was used for the following analysis, although other values up to one public bakery being the equivalent of ten private bakeries were explored).

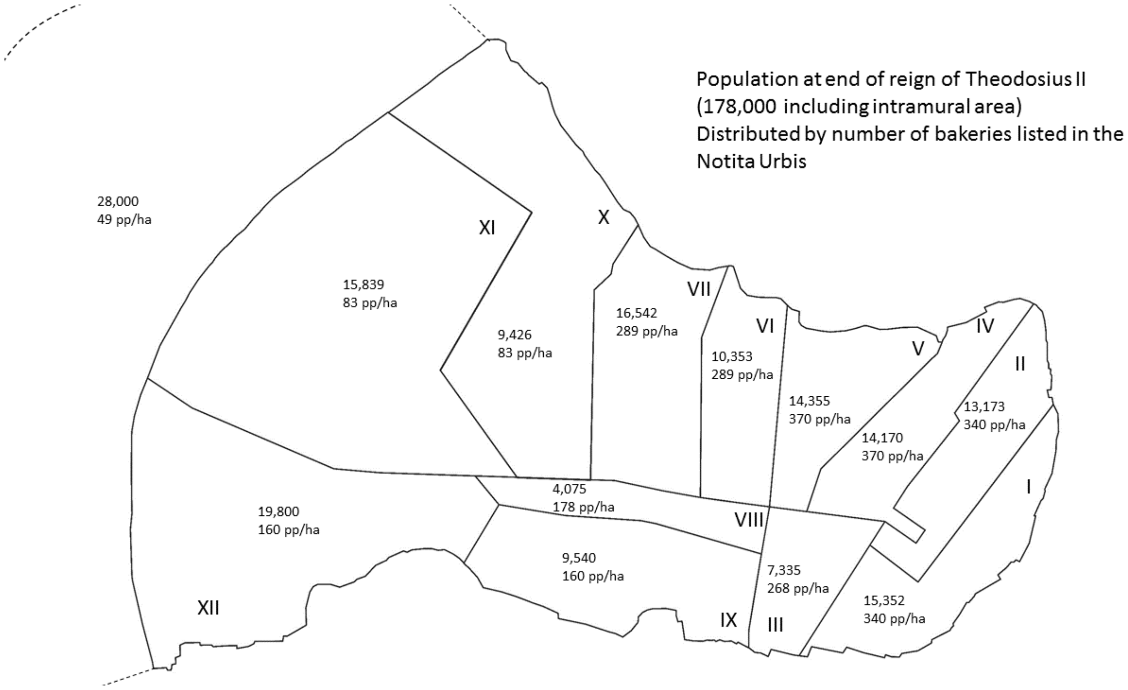


Private and public bakeries by region

| | | | | | |
|---|---|---|---|---|---|
| I | 15/4 | V | 2/7 | IX | 15/4 |
| II | 4/0 | VI | 17/1 | X | 16/2 |
| III | 9/0 | VII | 12/0 | XI | 3/1 |
| IV | 5/0 | VIII | 5/0 | XII | 5/0 |

Figure 5.9: Distribution of public and private bakeries listed in the *Notitia Urbis*.

Figure 5.8 shows that there is a high concentration of bakeries in Regions I, V, VI, X and IX which would result in high population figures for these areas. However the regions are only conceptual boundaries, not physical, so it would be unwise to consider each region entirely in isolation. It would be logical for someone living in Region VIII to obtain their bread from a bakery in neighbouring Region IX or, likewise, for some of the population in Region II and IV to travel to Regions I and V. So some regions can be considered as strongly linked, particularly when there is a region with a relatively low number of bakeries (such as Region II) alongside another with a high number of bakeries (such as Region I). The following regions were considered linked in the determination of population distribution: Regions I and II, Regions IV and V, Regions VI and VII, Regions IX and XII, and Regions X and XI.



Population at end of reign of Theodosius II (178,000 including intramural area) Distributed by number of bakeries listed in the Notita Urbis

Figure 5.9: Proposed 5th century population distribution (and density) based on the distribution of public and private bakeries

Figure 5.9 illustrates how the population is distributed when the relevant regions are linked and one public bakery is weighted to equal four private bakeries (the calculations for values shown in Figure 5.9 are included in Appendix A). What emerges is a more nuanced version of Jacoby's model with population densities gradually decreasing as you move towards the periphery of the city. The oldest parts of the city are the most densely populated, followed by the areas around the harbours and finally the large regions bordering the Constantinian Wall and the intramural area are the most sparsely populated. However at this point in time the water supply network was still under construction with some key cisterns not yet constructed (including the Basilica cistern and the open cisterns Aspar and Mokios).

### Projecting population density into the 6th century

The last of Jacoby's population estimates, for 541 AD, represents the point when both the population and the water supply infrastructure were at a peak. There is not a contemporary text on bakeries or other amenities for the 6th century population and it would be excessively simplistic to merely scale up each regional population to suit the increased total figure. It is much more likely that the outer regions (IX, X, XI & XII) would experience greater growth than the inner regions, simply because there would be more available space to grow into. These regions, particularly Regions X, XI and XII, would also have benefited from improved water supply infrastructure by the mid-6th century – the Mokios cistern turning the *xerolophos*, the dry hill, into a much more habitable area. Jacoby (1961) uses a maximum population density of 500 pp/ha based in part on the maximum density of 400 pp/ha for the walled city of Florence in the Middle Ages.

The population total doubles between the early fifth and mid sixth centuries; the proposed distribution of this increased population is shown in Figure 5.10. If doubling the population density resulted in a density of over 500 p/ha the region was capped at 500 p/ha (Regions I-VII) the other regions were then assigned either a low (x 2), medium (x 2.5) or high (x 3) growth rate and the remainder of the population located in the intramural region. Region VIII was considered to be an area of relatively low growth as it is a relatively small constrained site and already had a significant number of public facilities; Regions IX, X and XII with good access to both the coast and the major roads entering the city were considered as high growth areas; and Region XI with good road access but no coastline and the Lycus valley was considered a medium growth area. If we consider the modern perspective, a peak population of 500 pp/ha is roughly equivalent to Mexico City, significantly more than London (approx. 175 pp/ha) but considerably less than modern Istanbul's peak density of approximately 770 pp/ha (LSE Urban Age Cities Compared, n.d.).

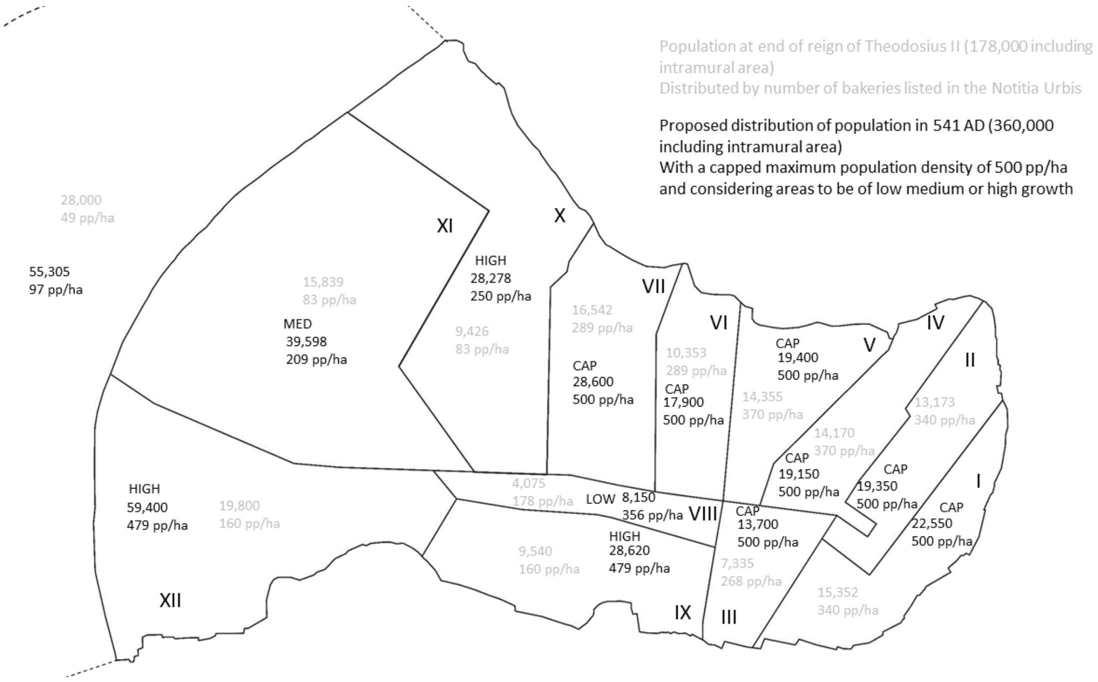


Figure 5.10: Proposed 6th century population distribution showing eastern regions reaching maximum population density and higher growth rates in the western regions.

## 5.4.5 Representing water demand in the model

Although there is enough evidence to establish that water demand in Constantinople was varied and complex, it is insufficient to generate a model of water use that represents the many water uses and users individually. Instead, a more general model of water use, focused around the domestic population, will be incorporated into the wider system model. It is assumed that water for commercial, industrial and some civic purposes can be incorporated into a single value and that the distribution of the domestic population will reflect the distribution of these other water users. As particularly high-demand water users, the public baths and Great Palace are represented individually in the model, rather than distributed across the population. Additionally, there is scope to include high-demand users associated with each of the large open-air cisterns which provides a tool for exploring the possibility that these larger cisterns were built specifically to supply industrial or agricultural uses.

## 5.5 Summary

The mapping and three-dimensional model created underpin and inform the consideration of both inflow and demand, as well as being critical to the development of the physical network discussed in the next chapter. The inflow and water demand will be directly incorporated into the system-wide model as the following parameters.

There are potentially four sources of water entering the city, from springs and rainfall, although only three sources are considered in the model:

- The Aqueduct of Hadrian relied on sources in the forest of Belgrad to the north of the city and Ottoman records of the Kırkçeşme system allow a basic estimate of daily flow to be made. A flat year-round rate of 9332 $m^3$/day will be used in the model.
- The Aqueduct of Valens, investigated in a parallel study, was more complex with multiple springs feeding into two possible channel arrangements. These channel arrangements combined with modern rainfall records and a spring flow study allow 24 different flow possibilities to be characterised. Each potential inflow will be investigated using the model.
- Rainwater harvesting was not the primary source of water for the cisterns but may have provided supplementary flow where it could be collected conveniently. For this study, supplementary rainwater is not considered as a water source in the model.
- The Mokios cistern and other smaller cisterns on Hill Seven, isolated from the rest of the city by the Lycus valley, may have been fed by a branch of the Aqueduct of Valens or by a separate aqueduct that tapped the low-yield Halkalı springs. The model will have two layout options, one with the Hill Seven cisterns fed by the Aqueduct of Valens inflow,

and the second with the cisterns fed by a flat year-round rate of 4212 $m^3$/day.

Water demand will focus on population, with individual consumption assumed to incorporate the majority of other water uses. Jacoby's (1961) population total of 180,000 in the 5th century and 360,000 in the 6th century based on densities in walled cities is used as a base to create a population distribution for the water demand model. The distribution for the 5th century population uses the private and public bakery data in the *Notitia Urbis*, modified to allow travel and interconnection between the regions. The 6th century population distribution was created based on a maximum population density of 500 p/ha and growth into the outer regions of the city. The *per capita* water demand is supplemented by demand from the eight public baths and the Great Palace. For simplicity the public baths are assumed to be the same size and use 4000 $m^3$ water per day in two 2000 $m^3$ batches at 6am and 3pm. The Great Palace is assumed to have a constant water demand of 6 $m^3$/hr.

The inflow and demand are the start and end points of the water supply system. In between and connecting them, is the physical distribution infrastructure: the network of cisterns, channels and control mechanisms that will be investigated in detail in Chapter 6.

# Reimagining the water supply system: the physical network

The many cisterns of Constantinople – aqueduct routes within the city – regulating the distribution – joining it all together

## 6.1 Introduction

The distribution network forms the heart of the water supply system, directing the inflow to where it will be used. This chapter focuses on the elements of the physical network that combined to deliver water from the aqueducts to the general population: storage in cisterns, conveyance by channels and pipes, and regulation by control mechanisms. These elements are considered in turn, examining the available evidence, and previous interpretations of it, from an engineering perspective.

Considered together, these elements enable the creation of the reimagined network, which is a fundamental part of the agent-based model presented in Chapter 7. This model will bring together the inflow, physical infrastructure and water demand in order to understand the operation of the system. The process of developing the reimagined network involves examining the available evidence of each element from an engineering perspective, both for what it can tell us about the element itself and about the wider network which connected the elements. Although the evidence is sparse, in-depth consideration of individual components in the perspective of a wider picture generates a synthesised water supply network that can be described in some detail.

Parts of section 6.2 *The cisterns* were presented at the International Water Association (IWA) 2016 Water and wastewater in ancient civilisations conference and subsequently published in the IWA's Water Science and Technology: Water Supply journal (Ward *et al.* 2017). Parts of Section 6.3 *The route of the Aqueduct of Hadrian* and Section 6.4 *The route of the Aqueduct of Valens* were published in the Journal of Roman Archaeology (Ward, Crow and Crapper 2017). This chapter builds on the published material, offering broader and more detailed considerations of these areas and with a perspective that links this work of understanding the water supply to developing the design of the network and the creation of the system model discussed in Chapter Seven.

## 6.2 The cisterns

The centrepiece of the water supply system in Constantinople is the cistern, the man-made water storage structure that by their spread, size and number indicate a complex distribution network that would have required significant organisation and decision making in order to operate successfully. The shift towards storing water, and away from Rome's strategy of continually seeking new water sources, indicates both the pressure on water resources and an awareness of the limitations of the environment and its inability to provide the abundance of water expected for the imperial capital. Yet the continued construction of major water users, such as the 153 private baths in place by the early 5th century and eight known public baths in place by the 6th century and (Mundell Mango 2015, p. 138-140), indicates that the city of Constantinople did not want or need to curb water use.[46] Cisterns allowed the city to develop into a place praised for its water provision and resilient enough to survive centuries of change and turmoil.

Although scholars have long been interested in the cisterns of Constantinople, only relatively recently have studies revealed just how numerous they were. The two most recent and comprehensive works on the cisterns of Constantinople doubled the number of known cisterns in Constantinople to about 160. By combining these studies, the current investigation has established that there are at least 211 Byzantine-era cisterns.

The new longer list of cisterns has a greater geographical spread and more detail on size and era, making it possible to consider the water supply and its development more fully. Cisterns were an important component within the network, acting as end-points from which water could be accessed and, possibly, as the start point of a localised distribution network of fountains. The differences in storage volume and location suggest that cisterns were adapted to serve different functions and make the best use of local conditions and resources. Examining the distribution of cisterns in space, time and type offers a way of understanding the wider network of which the cisterns were a part.

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[46] Although, as Mundell Mango (2015, p. 138) notes, Constantinople lists only 153 small baths whereas Rome has 856. This is possibly an indication that some water use was controlled within the city.

### 6.2.1 Creating the long list

The two most recent and comprehensive studies of cisterns in Constantinople used different approaches but came to roughly the same conclusion about the total number of cisterns in the city. In Crow, Bardill and Bayliss (2008), Bardill prepared a concordance of 161 cisterns, bringing together references of Constantinople's cisterns in literature ranging from the 15th century through to 21st century, along with a small number of unpublished cisterns. Where possible these cisterns were mapped and given a reference code using Müller-Wiener's naming convention (used on his map in the 1977 Bildlexikon), which splits the historic city into a 7 x 10 grid and then numbers the cisterns within each grid square. More recently, Altuğ (2013) developed a catalogue of 158 Byzantine cisterns, comprising only those cisterns that could be mapped, either because something remained or sufficient modern records were available. Altuğ was able to access the Istanbul municipal records which yielded a number of cisterns that have not been published in academic literature. The focus of his work was to provide a catalogue that recorded both the location and current physical state of cisterns. Altuğ's criteria for inclusion were quite strict and result in the exclusion of several cisterns that are included in Bardill's concordance, including the cistern designated D5/4. It is first mentioned by Gilles (trans. Byrd 2008, p. 178-9), who suggests the foundations of an old cistern adjacent to the Ottoman leather market (Saraçhane) might be the Modestus Cistern noted in the 5th century *Notitia Urbis.* Forchheimer & Strzygowski (1893, p. 52), were able to recognise the cistern characteristics matching Gilles' description at the same leather market 350 years later. Today the only link we have is a street named Saraçhane in the vicinity of the Bozdoğan Kemeri and this was deemed insufficient for inclusion in his catalogue.

One of the first steps in this study was to compare and combine the two lists. The combination of the lists was based on a three-part process: potential matches between the lists were first identified visually by mapping, then the names of the cisterns, their references in the literature, and any available descriptions were compared, and finally any outstanding queries were discussed in a meeting with Kerim Altuğ in April 2015. Appendix B details the extended list of 211 cisterns that was the output of the task of combining the lists.

### Spatial comparison

The map that accompanied the cistern concordance (Crow, Bardill and Bayliss, 2008, Map 12) was available in an AutoCAD format (DWG file) without spatial referencing, along with a database with additional cistern information, mainly dimensions. Altuğ provided an ArcGIS map file with 5-m contours of the modern city and the cisterns of his catalogue (although the cisterns were included as graphics rather than as features). Creating features of both sets of data and setting them to the same coordinate system identified the majority of cisterns that were shared between both lists.

### Descriptive comparison

For a number of smaller cisterns where there was not a clear spatial match, comparing the names given in the two lists – which were often descriptive, for example, cistern in Molla Husrev Street – provided evidence for potential matches. Both lists provided references to the literature that mention the cistern and comparing these was useful when there was still uncertainty. This process also identified a small number of cisterns on the Bardill concordance that were doubles and a few that had been placed incorrectly on the map.

### The final list

The final list includes at least 211 cisterns,[47] two of these (F3/1 and F4/1) are on the Galata peninsula, with the remaining 209 on the main historic peninsula within the Theodosian Walls. Of the 211 cisterns, 97 were present on both lists, 61 were exclusive to Altuğ's catalogue and 53 were exclusive to Bardill's concordance. All of the cisterns from Altuğ's catalogue are included in the longer list, but a number of cisterns found only on Bardill's concordance are not included because there was insufficient evidence to place them, even roughly, on the map. These include six for which Forchheimer & Stryzgowski's (1893, p. 111-114) list of "untraceable or unenterable cisterns" is the most recent source and the description it provided was insufficient to either place them or rule out a match with other cisterns. These six cisterns should not be completely dismissed

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[47] A single entry, E5/13, covers several cisterns discovered during the construction of Istanbul university library, so the number of individual cisterns is slightly higher.

– Altuğ was able to identify D5/9 (Ref 136 in his catalogue) as Forchheimer & Strzygowski's cistern "m" (1893, p. 113).

## 6.2.2 Cistern distributions

With so many cisterns now identified, it is possible to go beyond considering the cisterns individually and examine what can be inferred from their distribution across a complex of critical aspects: location, time, volume, elevation and proximity.

### Distribution by location

Cisterns have been found throughout the city but are clearly more numerous in some areas. It is not known whether this reflects the reality of the Byzantine period or whether some areas with few cistern finds – such as the shore areas of Regions V and VI, and much of Region IX and Region XII – once had many more cisterns that have now been lost. It is worth noting that one of the areas of greatest cistern density – around Hill One – has been the area with the greatest protection from development (because of the Topkapı Palace). Discounting possible missing cisterns, and considering the 209 cisterns as a single group, the vast majority of the city within the Constantinian Wall is no more than 250 m from a cistern, with only some areas of Regions XI and XII slightly less well served, being no more than 500 m from a cistern. Much of the intramural area is also within 500 m of a cistern, the least well-served area being the high ground next to the Theodosian Wall on Hill Seven, which is 1300 m from the nearest cistern.

With reference to Map 6.1, we can see that with the exception of the three open air cisterns (and one large cistern associated with a monastery) all the early-era cisterns are located within the Constantinian wall, and most of these are in Regions I to VIII, which include the oldest and most densely populated areas of the city. Cisterns are generally in close proximity to the aqueducts – about 48% of cisterns are within 250 m of an aqueduct that is upslope of them (*i.e.* capable of supplying the cistern).[48] The largest concentration of cisterns not achieving

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[48] Based on the aqueduct routes proposed in Sections 6.3 and 6.4.

this proximity is on Hill One (whose supply arrangements will be discussed in section 6.6.1).

### Distribution by era

Altuğ (2013) classified the cisterns in his catalogue into three broad time periods: early era (4-7th centuries), middle era (8-12th centuries), and late era (13-15th centuries), and a fourth category where the time period is unknown. The concordance in Crow *et al.* (2008) does not include any dating information. Almost 40% of the cisterns are not attributed to a particular era, either because Altuğ was unable to determine the period or because the chronology of the cistern has not yet been systematically assessed (which is the case for the cisterns only in Bardill's 2008 concordance). The 80 cisterns of unknown or unassessed era are spread throughout the city. Some cisterns belonging to the unassessed list, such as D5/4 (Saraçhane assumed to be the Modestus cistern), are associated with the early period; however, for the majority there is currently no clear evidence for which period they belong to.[49]

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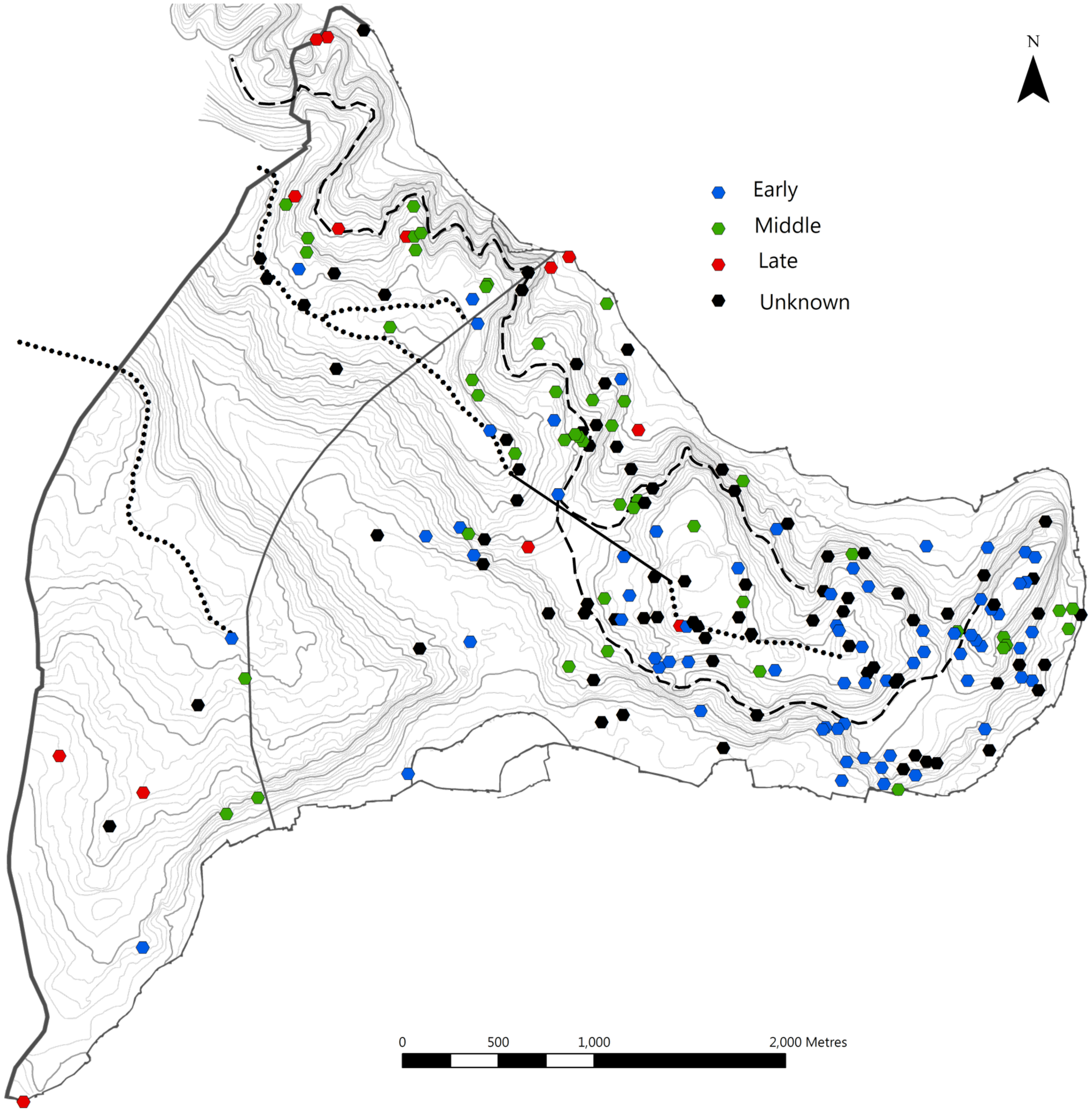
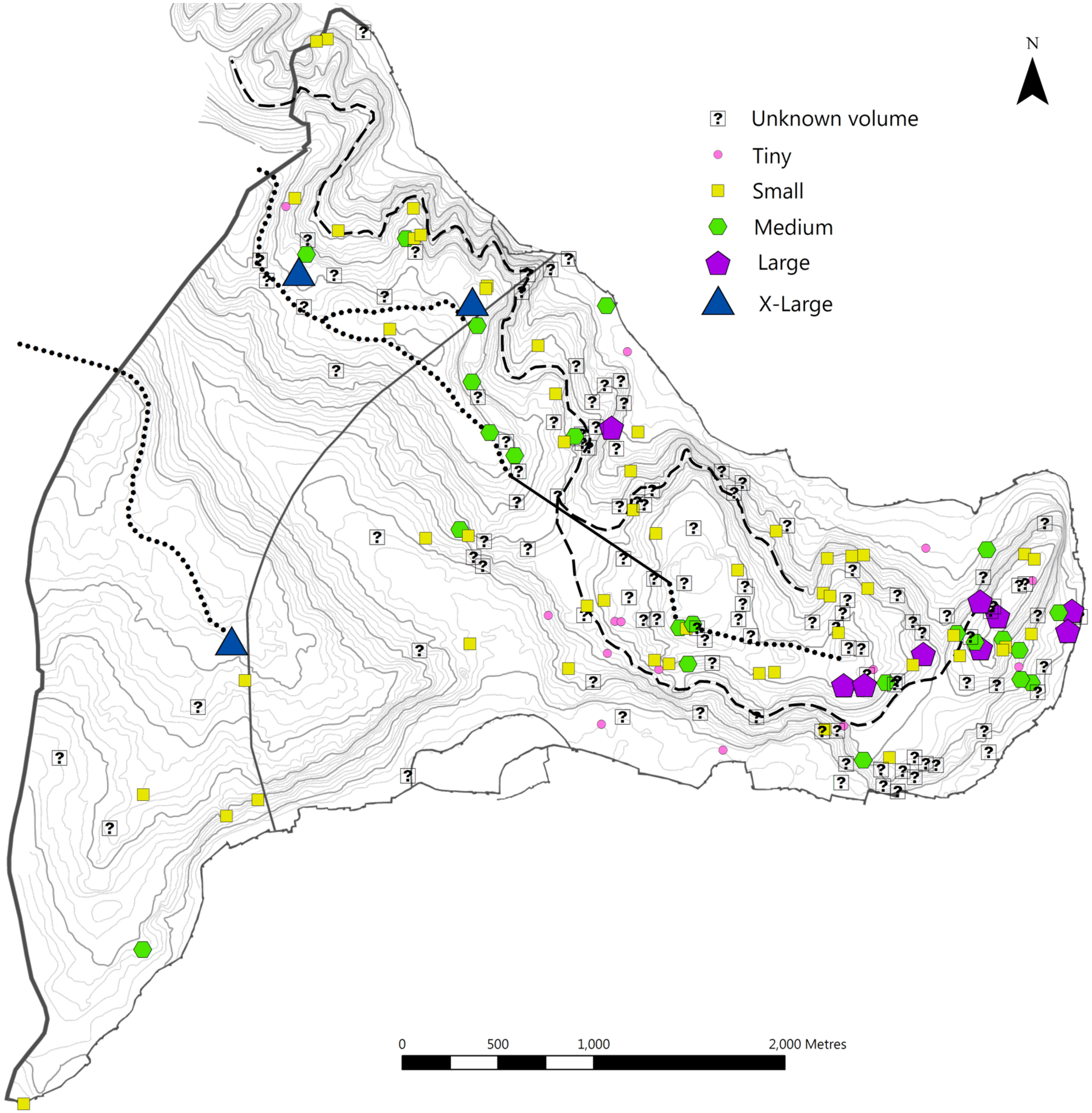
[49] I have not attempted to classify the cisterns in the unassessed period (even where the evidence of period is apparently clear) as this task is outwith the scope of an engineering investigation.



Map 6.1: Distribution of 209 cisterns from the combined list by era, using Altuğ (2013) dating convention and data. Early era cisterns belong to the 4-7th centuries, Middle era cisterns belong to the 8-12th centuries, and Late era cisterns belong to the 13-15th centuries. Cisterns where the era is unknown or has not been assessed are marked in black.



Map 6.2: Cistern distribution by volume, Tiny (<100 m$^3$) pink circles, Small (100-999 m$^3$) yellow squares, Medium (1000-4999 m$^3$) green hexagons, Large (5000-99999 m$^3$) purple pentagons, Extra Large (>100000 m$^3$) blue triangles, Unknown "?"

### Distribution by volume

There is volume data for just under half of the 209 cisterns, although in some cases only plan dimensions were available and the depth had to be estimated from photographs or by comparison with cisterns of similar size. The variation in cistern volume in Constantinople is enormous – from the known data it is possible to state that the cisterns range in size from under 2 $m^3$ to over 370,000 $m^3$. These volumes represent the upper bound of possible storage, as there is no clear evidence that cisterns were used up to the maximum possible capacity. The depth of a cistern might have been influenced by factors other than the need for storage: maintaining a particular ground level above the cistern combined with providing a meaningful amount of storage below the inflow point, which might be considerably below the ground level, could result in necessary space that would never be filled.

Table 6.1: Number of cisterns constructed by storage volume

| Range | Number of cisterns |
|---|---:|
| Tiny (< 100 $m^3$) | 14 |
| Small (100 - 999 $m^3$) | 52 |
| Medium (1000 - 4999 $m^3$) | 23 |
| Large (5000 - 99999 $m^3$) | 9 |
| Extra Large (> 100000 $m^3$) | 3 |
| Unknown volume | 110 |

I have classified the cisterns into different volume classes ranging from Tiny (volume < 100 $m^3$) to Extra-Large (volume > 100,000 $m^3$). The distribution of cisterns within these classes is shown in Table 6.1 and the distribution of era within each of those classes is illustrated in Figure 6.1. Cisterns belonging to every size class were constructed in the early era, which is unsurprising as this is believed to be the main period of cistern development. The maximum size of cistern constructed reduces in each period, with only small and medium sized cisterns constructed by the late era. Overall the number of Tiny cisterns is quite low. This could be because they are under-reported in the literature (being of, relatively speaking, such small size as to be considered insignificant) or because small-scale, individual cisterns were not widely considered necessary, as the city's network of cisterns were sufficient to ensure a water supply. There are unanswered questions about ownership of water infrastructure and the assumption has been made that all the cisterns with a volume greater than 100 m$^3$ were part of the public infrastructure.

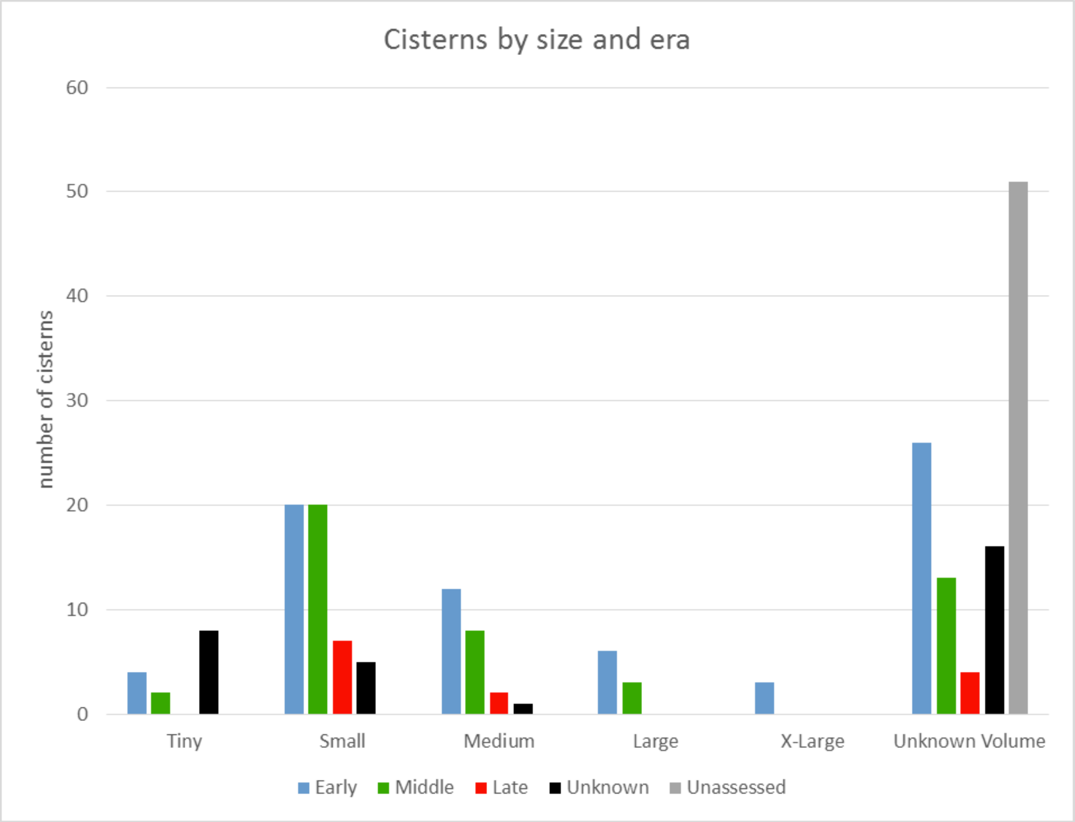


Figure 6.1: Cisterns by volume class and era

There is no standard measure in the literature for the size of cisterns, with most studies classifying cisterns on a scale relative to other cisterns in the same location. For example, Oğuz-Kırca (2016) classifies the 185 rock-cut medieval cisterns of Hasankeyf in south-eastern Turkey into six categories from 'very small' to 'extremely large'. However, the largest cistern, classified by Oğuz-Kırca as 'extremely large' only has a volume of 62 m$^3$, which would be classified as 'tiny' in my classification of Constantinople's cisterns and too small to be considered for inclusion in the network supply model.

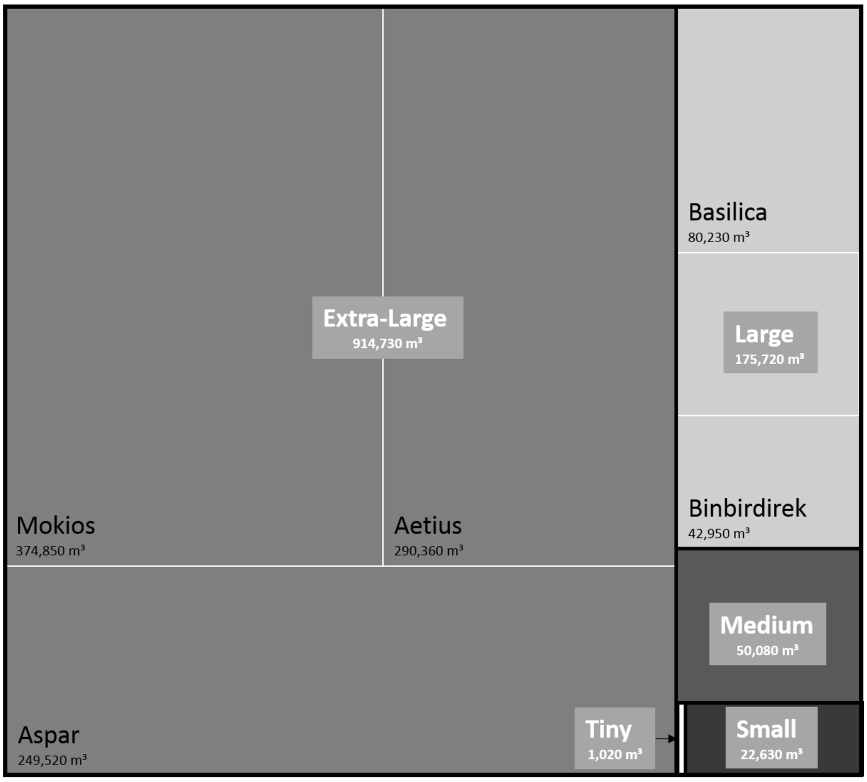


Figure 6.2: Distribution of 1.16 million m$^3$ of storage volume across the 102 cisterns with known dimensions. [50]

Figure 6.2 illustrates the proportion of storage, relative to the total known storage for the city, contributed by each size group and by certain named cisterns. The dominance of the three open-air cisterns is clear. Each of the remaining cisterns adds little to the total available storage (the tiny, small and medium groups have 90 cisterns but provide only 6% of the total storage), but they do expand the range of the network, creating structures from which water can be distributed locally. The decision to direct and store water across a network adds a layer of complexity not seen in Rome, where the abundance of water allowed the distribution system to operate with a continual overflow arrangement. The volume of unknown cisterns should not be dismissed as trivial, with at least two cisterns thought to be very large: the cistern on top of Hill Two of which only a 90-m long section of wall remains (identified as the cistern of Philoxenus by Bardill 1997, p. 69-75) and the Modestus cistern, tentatively identified by Forchheimer and Strzygowski (1893, p. 52) as a 154 m

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[50] The diagram was created in R using Tennekes (2016) Treemap Visualization and then adapted for clarity.

long and 90 m wide structure housing the Saraçhane market near the Bozdoğan Kemeri.

### Distribution by elevation

As well as the distribution of cisterns by location within the city it is possible, and worthwhile, to consider how cisterns are distributed by elevation. In a gravity fed system, water can be delivered with minimal work provided that it is higher than the desired destination. As soon as the water is lower, it needs to be lifted, either mechanically or by hand, which will tend to restrict the amount or the rate at which water is used. Aqueducts tend to arrive in Roman cities at the highest possible point in order to reduce the need for lifting devices, for example Pompeii, Ephesus and Thessaloniki (see Section 3.3). However, as shown in Figure 6.3, cisterns are found across each band of elevation in the city.

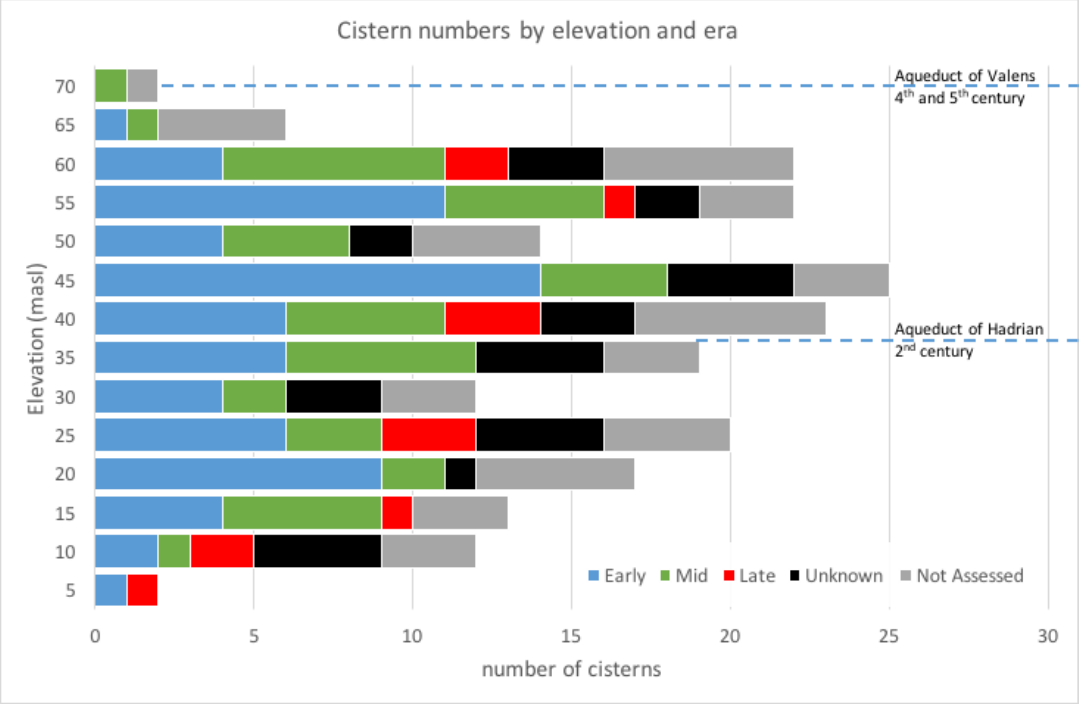

Figure 6.3: Number of cisterns in each 5-m band of elevation. Elevation of cistern is determined by the approximate ground level at the centre of the cistern. The era of construction is depicted by colour: early era cisterns (4-7th century) are blue, middle era cisterns (8-12th century) are green, late era (13-15th century) are red. Cisterns where the era is unknown or has not been assessed are shown in black and grey respectively. The approximate highest level of the aqueducts within the city are marked by the dashed lines.

The smallest number of cisterns are found in the highest bands, where it might be difficult to get water into the cistern, and the lowest bands, where water retrieved from the cistern would need to be lifted. Although there are more cisterns in the upper elevations, there are still a considerable number at lower levels – possibly this is influenced by the Aqueduct of Hadrian which was at a relatively low level within the city. However, the wide spread of cisterns across the elevation bands could also indicate that the cistern served a wider purpose than simply driving water through a downstream system. If cisterns were only located in the upper bands of elevation, the steep slopes from the ridge down to the sea could have resulted in the downstream water system being too highly pressured, resulting in greater risk of leaks and damage to pipes and higher flows at fountains and taps – cisterns at a range of elevations would enable pressure to be managed locally.

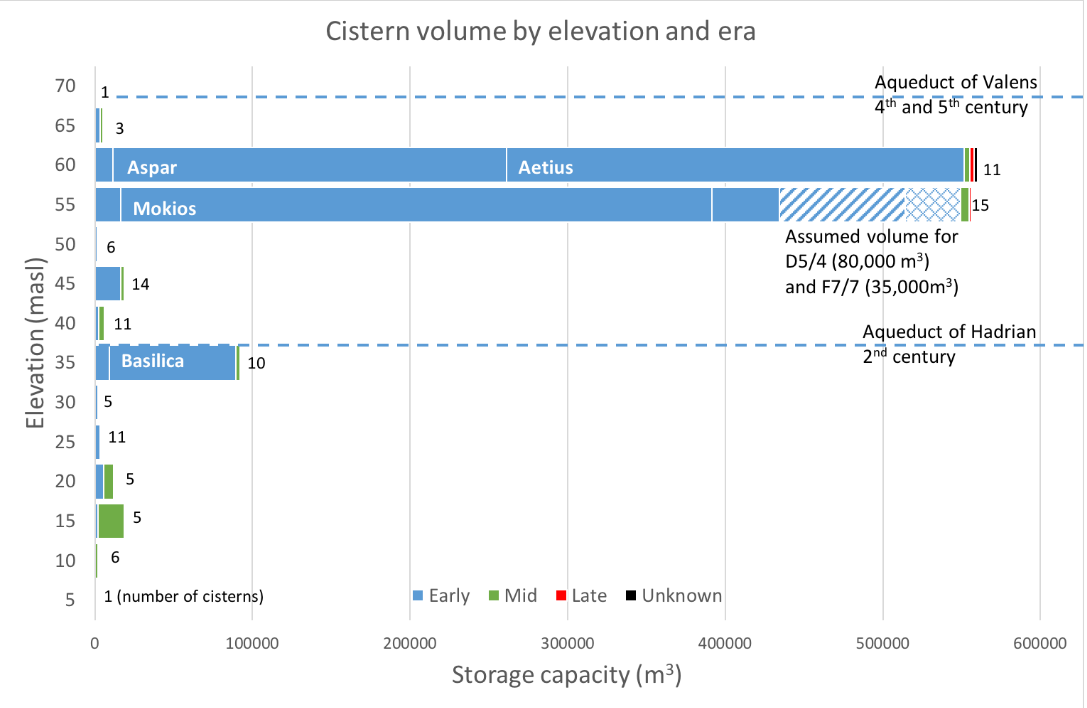

Figure 6.4: Storage volume by elevation and era

As cisterns in the city existed across a vast range of scales, it is important to consider not only the number of cisterns at each level but also the volume of storage that those cisterns provided. This must be drawn from the smaller dataset of cisterns for which volume is known or is estimable. The volume of 102 cisterns and assumed volume of two cisterns[51] (D5/4 Saraçhane and F7/7 Philoxenus) are included in Figure 6.4. It is immediately clear that the largest cisterns are disproportionately larger than anything else in the city. Most of the storage volume in the city is located between 50 and 60 masl, with a smaller but significant amount in the 30-35 masl band because of the presence of the Basilica cistern.

The highest elevations are in the areas closest to the Theodosian Wall, which as it was relatively sparsely populated, would be an ideal place to construct the very large open-air cisterns. However, as well as making the best use of available space, another advantage of having the storage at a high level is that it could be abstracted at a high-level relative to the rest of the city.

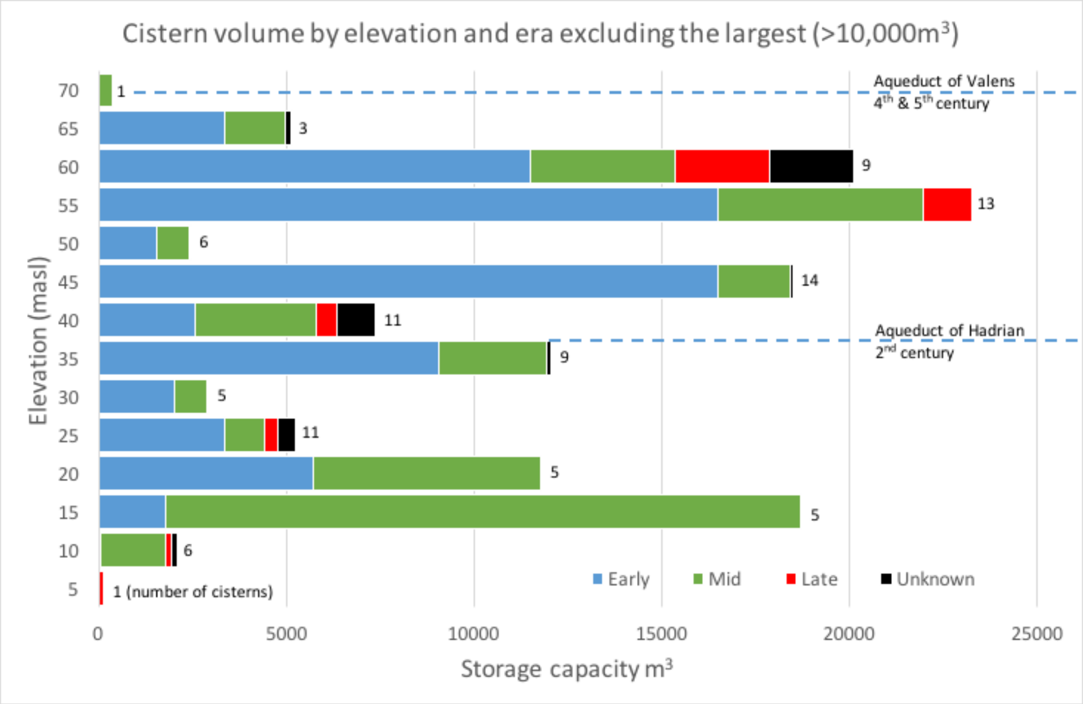

Figure 6.5: Cistern volume by elevation and era excluding the largest cisterns (those over 10,000 m³)

In Figure 6.4, the large cisterns overwhelm the smaller ones, obscuring what can be surmised from the patterns of construction, so Figure 6.5 also presents

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[51] A volume is included for these two cisterns because they are known to be large and there is some partial information to base the volume on. For D5/4 Saraçhane (the Modestus cistern), Forchheimer & Strzygowski (1893, p. 52) record walls of 154 m and 90 m. For F7/7 Philoxenus, a 90 m length of wall remains and a depth of at least 14 m has been recorded (Altuğ 2013 p. 258-9).

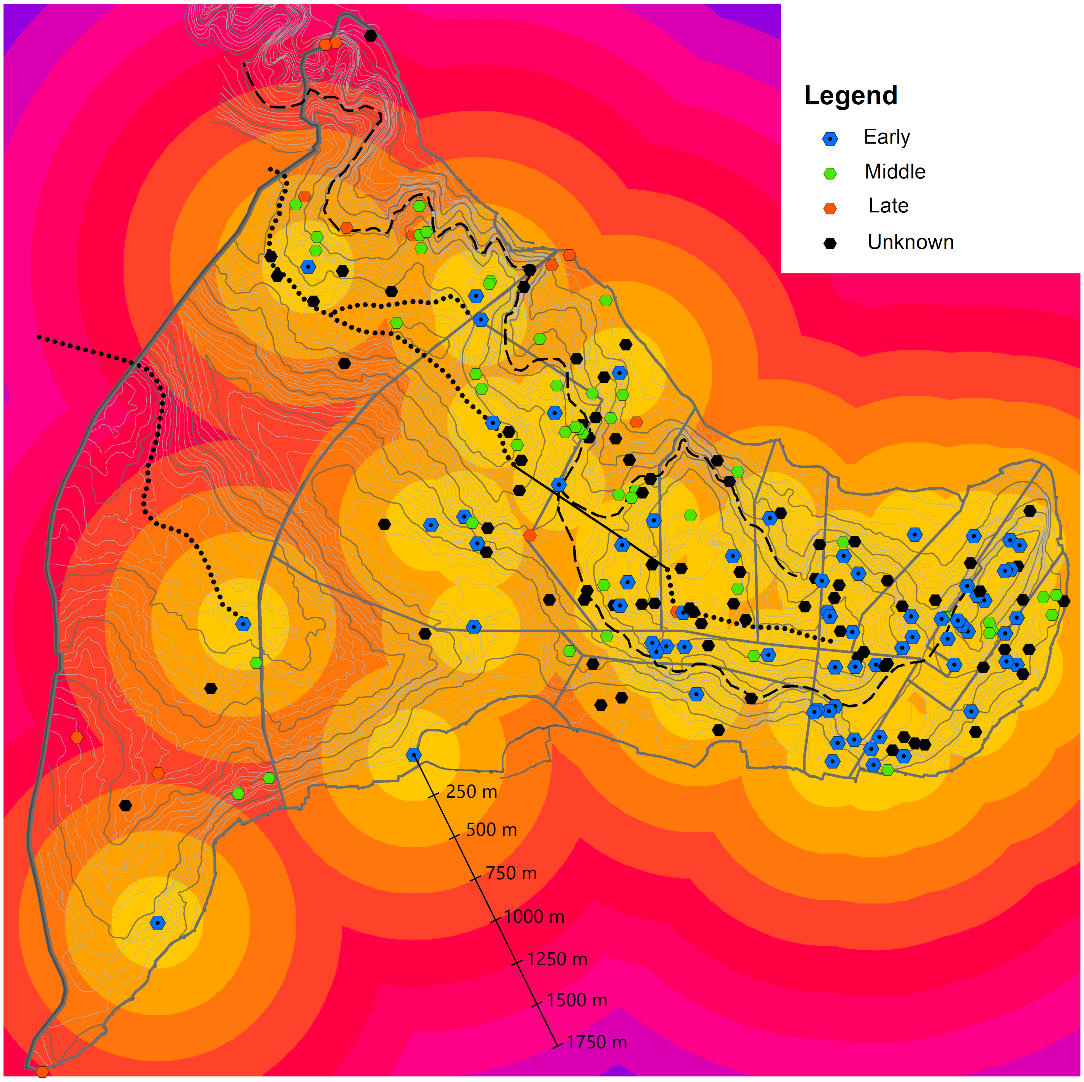
the storage volume and era of that storage for each 5 m elevation band but excludes all cisterns above 10,000 $m^3$ (Mokios, Aetius, Aspar, Basilica, Saraçhane, Binbirdirek and Philoxenus). With these excluded we can see that the majority of storage is still in the higher elevation bands, although there is a significant volume provided by middle era cisterns in the 10-15 m band. Much of this volume is in G6/16 and G7/18, respectively a five-storey palace and a monastery, the lower levels of which were used as cisterns, so the large storage volume at this elevation might be more expedient than strategic.

### Distribution of proximity to water

The discussions so far have focused on elements of cistern distribution – location, era, volume, and elevation – however the reality is more complex. Water was an essential used by everybody throughout the city every day. The absolute numbers of cisterns and their volumes do not provide a clear picture of the ease of access to water and how this varied for the population across the city. To build this picture we can start with initially considering the proximity of cisterns to each other and the network that this creates, and then progress to incorporating individual cistern volumes and the variations of population density (set out in Section 5.4.4).

Map 6.3 illustrates a Euclidean distance calculation that considers the 70 cisterns identified as belonging to the early era. These 70 cisterns provide a high level of coverage for the city: everywhere within the Constantinian Wall is within 750 metres of a cistern, all of Regions I-V are within 250 metres of a cistern and all of Regions VI-X are within 500 metres of a cistern. The modern minimum standard for collecting water is that people should be no more than 500 metres from their water collection point (Sphere handbook n.d.), most of the city already achieved this standard and, if we take into consideration that a local network of fountains can probably be associated with many cisterns, it is clear that the majority of people would not have to travel far to access water. Even on this basic analysis, there are indications that a planned and organised distribution network already existed in the early period.

Although the distance bands shown in Map 6.3 are based only on the early era, all the cisterns from each time period are shown. The 46 cisterns belonging to the middle period are located across the city. Those around Hills One, Two and Three are in close proximity to early era cisterns and do little to expand the accessibility of the network – these are perhaps replacing broken cisterns or strengthening provision by increasing storage volume. However, the other middle period cisterns tend to be located further from early era cisterns and therefore indicate expansion into new areas, particularly on the northern flanks of Hills Four, Five and Six.



Map 6.3: Distance to the nearest early era cistern. Background colouring shows distance from early era cisterns in 250 m bands, with cisterns from all eras displayed (blue = early, green = middle, red = late, black = unknown).

There are only 13 Late period cisterns, only one (on Hill Three) is located in an early-era 250-m distance band, the others are located in the 500, 750, 1000 and

1000+ m distance bands (although by the time the Late period cisterns were constructed the middle period cisterns would be in place, reducing some of the distance bands) which suggests that the cisterns were placed in areas of poorer provision to increase the coverage of the network. It also suggests that generally the cisterns already in place by this point were working adequately as the location of the late cisterns does not suggest the replacement of older, broken cisterns. Most of the late period cisterns are in the same area as the middle era cluster, along with three cisterns in the southern part of the intramural region. The cisterns where the era is unknown are spread evenly across the City, with most inside the Constantinian Walls.

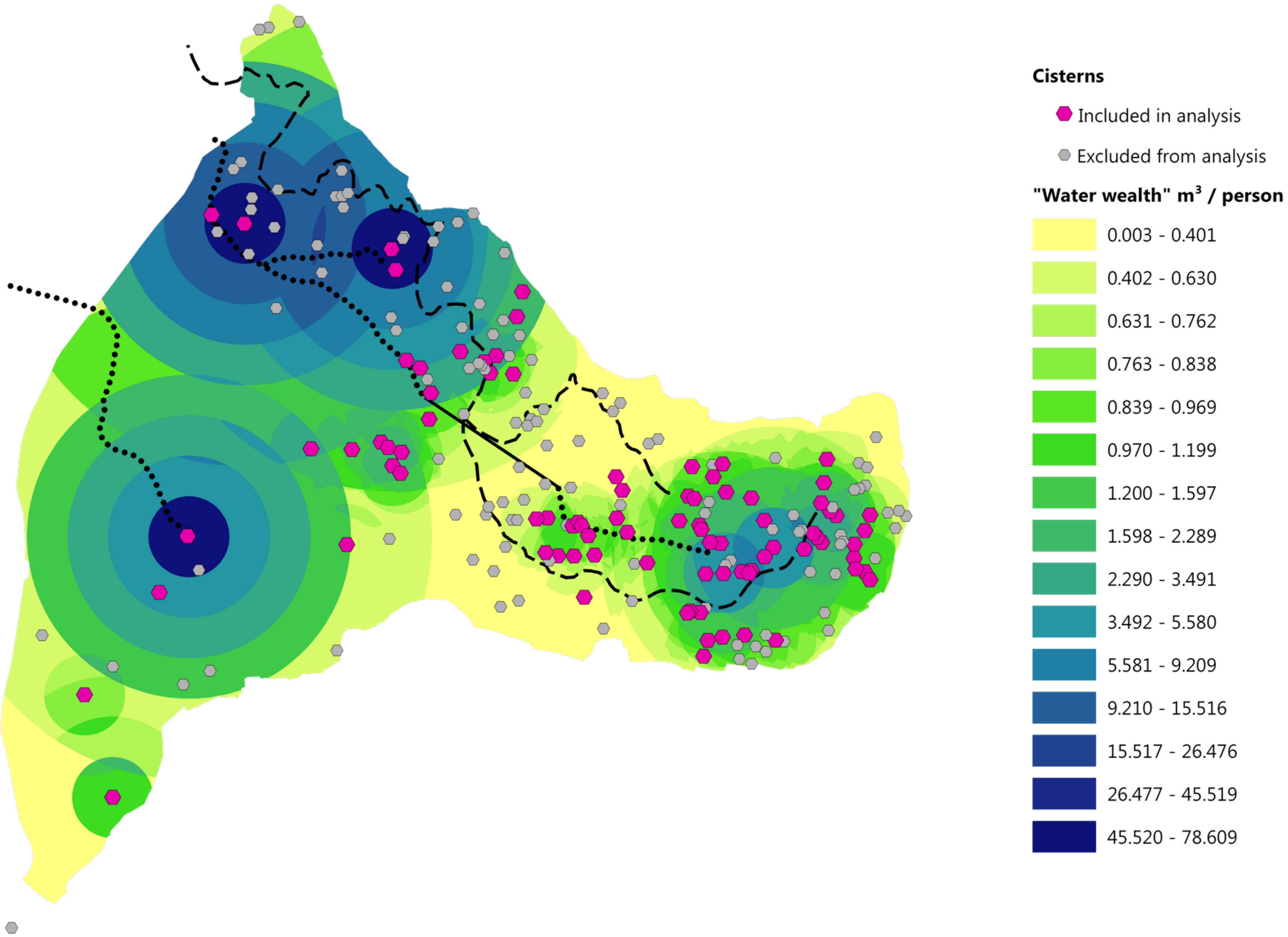
Proximity to a cistern does not tell the whole story: the number of people reliant on the cistern, its storage volume and the management of water into it also play a part. Map 6.4 displays the 'water wealth' of the population across the city, calculated as the total storage volume available per person from nearby cisterns. Each cistern has been given a sphere of influence depending on its size class and a weighted proportion of its volume is distributed among the population (with the population density distributed as discussed in Section 5.4.4 and illustrated in Figure 5.14). A fuller explanation of the development and production of this map is in Appendix C.

In Map 6.4 the enormous influence of the three open-air cisterns on the periphery of the city is clear: the areas immediately surrounding them are the 'wealthiest' in terms of water, with a combination of high storage volumes and very low population density. In the centre of the city the impact of the Basilica and Binbirdirek cisterns is not so apparent, as the much larger population in this area offsets the high volumes to give an area of less water wealth. In between these two areas is an area of low water wealth, where the available water storage per person is much lower than elsewhere in the city.

The data shown in Map 6.4 is complex and supports a number of interpretations. Firstly, the area of low water wealth on the periphery of groups of cisterns on Hills Two, Three and Four has no cisterns that were included in the analysis. The cisterns shown in grey on Map 6.4 were omitted from the analysis for this map either because of their time period (they were constructed later) or their size (too small). The later cisterns may be a response to this lack of water wealth. Secondly, Map 6.4 is unable to take account of the dynamic nature of a water supply system; it offers only a picture of available water storage per person, but not how readily that was replenished. The provision in the area of low water wealth could have been adequate if the cisterns that surrounded it were reliably filled. Thirdly, the analysis behind Map 6.4 does not incorporate the needs of the baths which might result in lowering of storage availability in some areas. Map 6.4 is also unable to capture the potential for provision directly from the aqueducts – the projected route of the two branches of the Aqueduct of Hadrian (see Section 6.2.4) cuts through the low water wealth area and could perhaps have supplied these areas directly, as seen in Rome and other cities.

It is interesting to note that the variation in water storage per person across the city could also be interpreted as contrasting supply strategies for different phases of the supply network. If we exclude the largest, open-air cisterns, whose storage is so large that it clearly serves a purpose beyond supplying the needs of the surrounding population, the greatest storage per person is at the end of the supply network and the lowest storage per person is in the middle and upper network areas. Given that water must flow through the upper and middle network before reaching the end of the supply network, it is the end that is at greatest risk of not receiving water (as upstream areas have first access). The greater storage may be a way of mitigating this risk.

One of the major implications of the variation in water storage per person across the city is the particular importance of management in this water system. This is discussed further in Section 6.5 where the physical mechanisms allowing water regulation are investigated. There are few remains of this type from Constantinople but as shown here, their presence can be inferred from consideration of the wider network.



Map 6.4: Water wealth of the population

### 6.2.3 The largest cisterns

The three largest cisterns – Mokios, Aetius and Aspar – provide over three quarters of the water storage within the city. The cisterns of Modestus and Arcadiaca, presumed to be very large, were also located towards the periphery of the city, and could be added to the category of largest cisterns. More centrally, the Basilica, Binbirdirek and Philoxenus (F7/7) cisterns are significantly larger than their neighbours.

The function, or range of functions, these large cisterns served is not clear. As discussed in the previous section on Map 6.4, the water storage in Aspar, Aetius and Mokios is far in excess of what is needed for the small population that had easy access to them. They might serve as strategic reserves to be brought into service at times of crisis; provide water for special high-volume use such as irrigation or industrial mills; or be an integral part of the regular network, supplying water to downstream cisterns.

The position of Aetius and Aspar offers some clues to their use. Both are located in relatively close proximity on the northern slopes of the ridge between Hill Five and Hill Six. As the land downslope of the cisterns falls steeply towards the sea it is unlikely to have been heavily cultivated and would not require significant irrigation water. However, the slope beneath the two cisterns does carry the Aqueduct of Hadrian. As the lowest levels of Aspar and Aetius are above the level of the aqueduct, it is possible that these cisterns were positioned and designed to allow water to be released from them into the lower aqueduct and conveyed into the heart of the city. The same argument might be made for the assumed large open-air cistern at Saraçhane (D5/4, the Modestus Cistern).

This in turn suggests one possible reason behind the construction of the Basilica cistern. Procopius states that the Basilica cistern was constructed in order to counter shortages of water during the summer months (*Buildings* 1.11.10-15 trans. Dewing & Downey 1940, 91-2). As at the time of its construction the city already had huge storage capacity in its open-air cisterns (over 900,000 $m^3$ in Aspar, Aetius, Mokios, and an unknown but substantial volume in Arcadius and Modestus) the Basilica's 80,000 $m^3$ was hardly a significant addition in terms of volume, unless the water in the open-air cisterns was never used for drinking (which seems unlikely in a period of shortage). However, it does significantly increase the storage volume in the centre of the city, where a significant proportion of the population could access it. The Basilica cistern was positioned so that it could be fed by the Aqueduct of Hadrian, however, as discussed in section 5.3.2, there is some evidence that flow was limited and therefore the excess available to store in the Basilica would be small – it would take a long time for the cistern to fill under this regime.[52] However, it is also possible that the Basilica cistern was constructed to receive water released from Aetius and Aspar into the Aqueduct of Hadrian. The remains of a control mechanism that could have been used for such a system are discussed in Section 6.5.1 Aspar 1. Releasing water from such a large cistern would be a difficult task – the flow released would be large relative to many of the cisterns in the city centre,[53] so having a large receiver at the other end (the Basilica cistern) would create a more straightforward operation and reduce the likelihood of wasting water (which might already be scarce if transfers were required).

This consideration of the role of the large cisterns does not offer a definitive conclusion. Each of the uses: strategic reserve, high-volume use, and supply to the downstream network, remains possible in combination or individually. This is further evidence that what was in place was used and operated as a system, with the largest cisterns offering flexibility in how and where water was used. To arrive at a fuller picture the insights gained by considering cisterns as an individual element need to be combined with similar work on the rest of the physical network to produce a dynamic, functioning model of the system. Although there is no evidence of the management element, it is suggested by analysis of the physical remains and textual evidence, and the model will enable it to be investigated.

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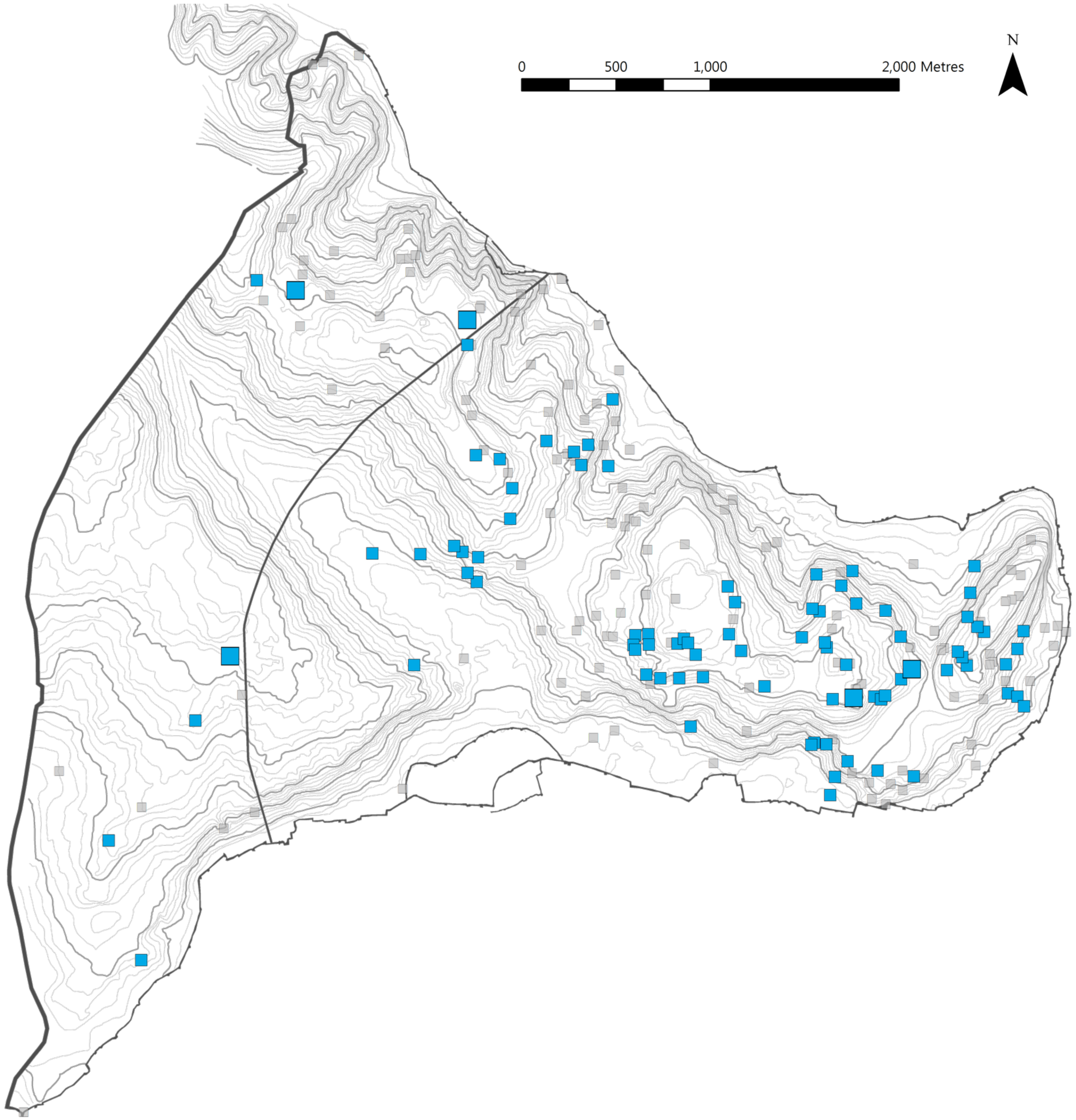
[52] Based on water entering the city through the Aqueduct of Hadrian from the Belgrad Forest, that is, not taking into consideration the possibility of the aqueduct being fed by the open-air cisterns.

[53] Without survey information of the Aspar 1 structure (see Section 6.5.1) it is only possible to give a tentative estimate of flow extraction. Assuming an opening 600 mm wide and 800 mm high, a water surface 7 m above the soffit of the opening and an assumed coefficient of discharge of 0.6, gives a flow of approximately 3.5 $m^3/s$. The opening would need to be open for less than a minute to overwhelm many cisterns in the Small category.



Map 6.5: Cisterns included in the model of the water supply system (with volume either greater than 100 m$^3$ or unknown, and belonging to the early period or of unknown /unassessed period).

### 6.2.4 Cisterns included in the model of the water supply system

The cisterns cannot be understood in isolation – they form an integral part of the water supply system. The connection of these cisterns into a network is established in the following sections by reconsidering the routes of the two main aqueducts, the means of regulating flow and then the potential connections between aqueduct, control mechanism and cisterns.  The water supply system is investigated as a whole in the next chapter where the results of the mass-balance, agent-based model of the system are presented.

Although all the known cisterns have been considered in various ways within this section, only some of them will be incorporated in the working model of the whole water supply system. This model seeks to represent the city as it was in the mid-6th century because it is a period of peak population and the point when it is assumed that the essentials of the water supply system was complete. Of the 209 cisterns identified on the historic peninsula those identified as belonging to the middle and late eras will be omitted. It is assumed that the cisterns of unknown or unassigned date should be considered for inclusion in the model as they are most likely to belong to the largest period of construction building, which was the early period.

Practically, managing the flows into the smaller cisterns would be difficult. In early versions of the model, two of the Tiny cisterns (E4/2 and G7/8, with capacities of 50 and 74 $m^3$ respectively) were included, however, they proved very difficult to manage, constantly shifting between full and empty and causing almost constant service failures. This might suggest that access to smaller cisterns was restricted to a small number of users, which would create an appropriate level of water demand and enable them to operate consistently. The model does not currently have the capacity for such nuanced management rules, therefore, only cisterns with volume greater than 100 $m^3$ (Small, Medium, Large and Extra-Large categories) are included: all cisterns categorised as Tiny are excluded.

From this smaller group of possible cisterns to include, the final selection of 87 were based on ease of connection into the main aqueducts (discussed in Section 6.6). The cisterns included in the model are illustrated in Map 6.5. Of these, 43 have volumes that are known or estimatable (for instance where some dimensions, but not all, are known) and 44 have no volume data associated with them.

## 6.3 The route of the Aqueduct of Hadrian

The cisterns cannot be understood in isolation. As key components of a water supply system, they must be seen in relation to the other parts of that system, principally the two main aqueducts, then any potential connections between them. The two aqueducts form the main spines of the distribution system, every part of which depended on one or the other of them. Therefore, the routes that they took within the city are key to understanding the wider network. However, the routes of both aqueducts, as presently understood, are problematic in certain aspects and need to be reconsidered.

As there is no confirmed physical evidence of the Aqueduct of Hadrian within the city and only limited evidence of the Aqueduct of Valens, all that is known of the route of the former has been inferred from other historical sources which were discussed in Chapter 2: law codes limiting water to specific users and histories which specifically link the Basilica cistern with the Aqueduct of Hadrian.

This section looks at what can be inferred about the aqueduct route from studying the topography of Byzantium, the settlement it was built to serve; the positions of the structures known to be fed by the aqueduct and the structures that can be inferred to have been fed by the aqueduct; and the Ottoman system that eventually replaced the Aqueduct of Hadrian. Here the principles of hydraulic engineering offer an additional source of inference from which new insights can be gleaned.

The Aqueduct of Hadrian is assumed to have been constructed in the mid-2nd century, when Hadrian visited the region (Crow *et al.* 2008, p. 10-13). This aqueduct supplied water first to Byzantium then Constantinople before being replaced in the 16th century by the Ottoman Kırkçeşme water supply system. The aqueduct provided Constantinople's main water supply for the first few decades after the city was established in 330 and was also the sole supply for

140 years in the 7th and 8th centuries, after the Aqueduct of Valens was purposely cut by the Avars in 626 and was not restored till 765 (Crow *et al.* 2008, p. 19-20). Despite the key role of the aqueduct, little is known about it. There is no confirmed physical evidence of the channel within the city. The chief source of data is textual: the Aqueduct of Hadrian was used to supply the Imperial Palace, the Baths of Achilles and possibly another of the public baths (Cod. Just. 11.42.6 trans. Frier et al 2016), and the Basilica cistern, constructed in the mid-6th century was fed by the Aqueduct of Hadrian (Malalas *Chronicle* 18.17 trans. Jeffreys *et al.* 1986). Additionally, there is the association between the Aqueduct of Hadrian and the Ottoman Kırkçeşme system (previously discussed in section 5.3.2). They are thought to have the same water source, in the Belgrad Forest, and follow a similar route from there into the city so that the elevation of the Kırkçeşme system as it crosses the line of the Theodosian wall, about 34 m, has been taken as a likely entry level for the Aqueduct of Hadrian at the same point.

This information led Crow, Bardill and Bayliss (2008, Map 12 and p. 114-7) to project the route of the aqueduct across the northern slopes of the main ridge comprising Hills Six to Two before splitting into two branches, the northern branch traversing the north-west slope of Hill One and the other branch turning south between the Hagia Sophia and the Basilica cistern, crossing the flatter area between Hills One and Two, towards the Imperial Palace and continuing west, through the Sphendone of the Hippodrome and terminating on the steep southern slope below the Forum of Constantine. This route is illustrated in Figure 2.2 in Chapter 2.

However, aspects of this route are problematic. For any gravity-fed system the elevation at entry cannot be exceeded (and must therefore be maximised to ensure the widest possible distribution), while the end point of such a system fixes its lowest elevation; between those two points, the trend must necessarily be downhill. Since the system works by gravity alone, the initial entry elevation of the channel dictates all the subsequent locations that can be fed from it, while the elevation of each location dictates the sequence in which each was fed. With this in mind, we must consider the evidence of what locations within the city were fed by the Hadrianic line (and where it is thought to have terminated).

### 6.3.1 Pre-Constantinople – evidence of the water supply to Byzantium

The Aqueduct of Hadrian was operated, repaired and maintained for over a millennium, from its construction in the 2nd century through to the major renovation and replacement by the Ottomans in the 16th century. To have served the city for such a long period of time indicates that the channel was still relatively accessible (for maintenance and repairs) despite the enormous changes taking place around the coastline and to the topography of the peninsula. The original town occupied only the end of the peninsula that would become Constantinople and was bounded by a defensive wall that crossed the second hill from coast to coast (as shown in Figure 2.1 in Chapter 2, and Mango 1985, p. 14). The majority of the population was probably focused in the north-facing valley between Hills One and Two around the harbour and Strategion (now occupied by Sirkeci Station). This area is relatively low lying and could be served by an aqueduct arriving at around 31 masl. However, if water did arrive in the central area of Byzantium at this elevation, at least a third of the town's area, which was above this elevation could not have been supplied with running water.

As seen in Section 3.3, water provided by Roman aqueducts was typically distributed from the highest point of the town in order to maximise the area that could be supplied. For Byzantium, this would have been at about 55 masl, at the point which later became the Forum of Constantine. To achieve this, the Aqueduct of Hadrian would require a major bridge or inverted siphon to cross the valley between Hills Three and Four (where the Bozdoğan Kemeri stands – see Figure 2.1), but no evidence has been found or is attested in ancient accounts. If the population of Byzantium was concentrated on the lower slopes, a crossing structure, both costly and a security weakness (since it exposed a vital lifeline into the town), may have been considered unnecessary. Nonetheless, it is likely that the builders aimed for as high an entry point to the town as practical, making the crossing of the valley between Hills Three and Four critical. As the lowest ground level of this valley is estimated to have been about 35-36 masl in the Byzantine period,[54] this fixes a probable maximum invert level at this point as 34 masl, assuming a cut-and-cover type construction rather than a method which would expose the channel above ground, making it vulnerable to tampering.

## 6.3.2 The evidence of Byzantine Constantinople

### Supplying the Imperial Palace and Zeuxippos Baths

In early Constantinople, the Aqueduct of Hadrian fed, amongst other sites, the Imperial Palace, which was located on the south side of the platform between Hills One and Two. The maximum ground level is about 30 masl where the palace lies adjacent to the Hippodrome and Zeuxippos Baths, with ground levels falling to the south and east, so that if the channel was at a level sufficient to supply the platform level it would have been capable of supplying the Imperial Palace. Although there is no text linking the Zeuxippos Baths and the Aqueduct of Hadrian, it appears clear that this is how the baths were supplied with water, which adds further evidence to the route of the aqueduct within the city. The Zeuxippos Baths, a centrepiece of the city, would have required access to an aqueduct to provide sufficient water.[55] The Baths' origins are unclear, some texts attributing the baths to Severus and others to Constantine, but in either case they are undoubtedly an early feature of the city (Mundell Mango 2016, p. 136) and should therefore be linked to the Aqueduct of Hadrian, not the Aqueduct of Valens (which only arrived in 373). The baths were partially excavated in the 1920s as part of the investigations into the Hippodrome (Casson, Talbot Rice & Jones 1928). They lie adjacent to the Hippodrome at a level of 30 masl, dropping slightly to the east (Casson *et al.* 1928, p. 21). If this is the ground level in the baths, we would expect the water supply to arrive at a higher level – at least 32 masl – to allow it to flow through boilers, operate fountains and possibly showers.

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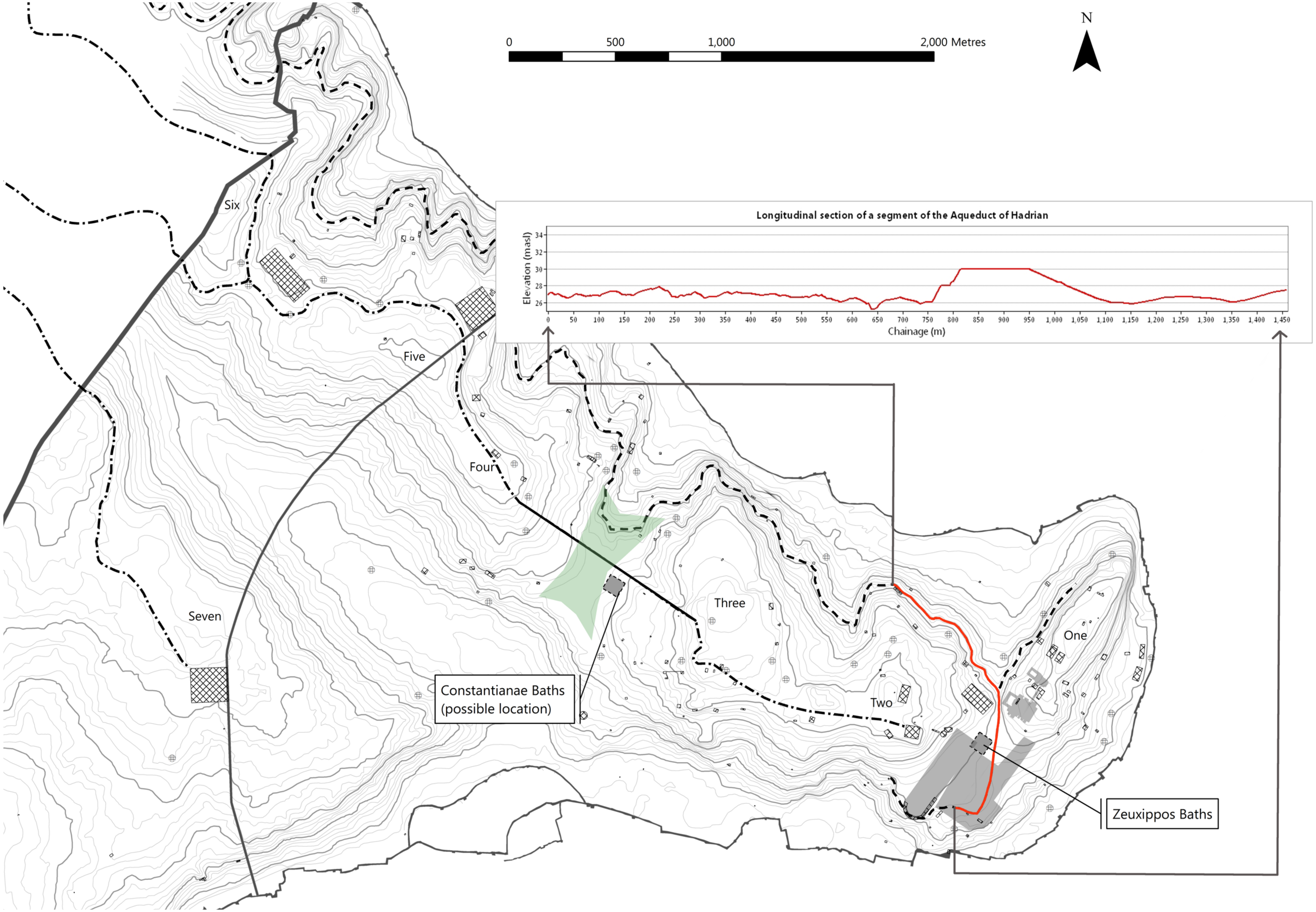
[54] The level from Müller-Wiener's (1977) map, using the contours of the 1920s, is 41 masl. In "sounding B" Harrison (1986, p. 13-14), found the foundations of Bozdoğan Kemeri to be 6.5 m below the existing ground level.

[55] As Hodge (2002) said, many Roman aqueducts were constructed in order to supply public baths; a more convenient, flowing supply was merely a side benefit. For example, the restoration of the *Aqua Marcia* and construction of the branch *Aqua Antoniniana* for the Baths of Caracalla (DeLaine 1997, p. 16).

The route proposed for the Aqueduct of Hadrian by Crow *et al.* (2008) is shown in Figure 2.2. However, using the digitised Müller-Wiener map that has been adjusted to include known Constantinople ground levels (discussed in Section 5.2), if we take a longitudinal section through this route (see the insert in Map 6.6), we find that between chainage 750 m and 800 m the channel must rise over 4 m in order to reach the area with the Zeuxippos Baths and Imperial Palace, which is impossible. Further, at the critical area between Hills Three and Four, where the probable invert level to maximise coverage of Byzantium was identified as about 34 masl, the level of this route is below 30 masl (indicated on Map 6.6 in green). Therefore, it is clear that the route projected by Crow *et al.* (2008) cannot be reconciled with the evidence, so the actual route must be either a modified, higher version or a different route altogether.



Map 6.6: Longitudinal section through Aqueduct of Hadrian route proposed in Crow, Bardill & Bayliss (2008)

### Supplying the Constantianae Baths

It is less clear-cut but still possible that the Aqueduct of Hadrian may also have supplied, or been intended to supply, the Constantianae Baths which are believed to lie near the modern Belediye building on the southwestern flank of Hill Three (Mango 1985, p. 41). Construction of these baths began in 345 (*Chronicon Pascale* 534 cited in Crow *et al.* 2008, p. 223) whereas the Aqueduct of Valens did not arrive at the city until 373, and it is implausible that construction would start so far in advance of the water supply on which the baths were reliant. Even the time to conceive, design and build the enormous Caracalla baths in Rome was no more than seven years (DeLaine 1997, p. 183). It seems more likely that the baths were constructed only where an adequate supply of water could be guaranteed, and when construction started, this could only have been the Aqueduct of Hadrian. In the event, however, the baths were not completed until 427 (Marcellinus, *Chronicle* 427 and *Chronicon Pascale* 581-82, both cited in Crow *et al.* 2008, p. 229). The 80-year construction period is extraordinary and must cast some doubt on the Aqueduct of Hadrian being the eventual supplier to the working baths. Still, whatever the circumstances of the baths' construction, we must consider the baths being fed by the Aqueduct of Hadrian as a strong possibility; the alternative is a bath that was intended to have been completed far in advance of the water supply, meaning that it would be empty and unused for 20 years before the arrival of the Aqueduct of Valens. Accepting, then, that the Aqueduct of Hadrian was capable of supplying the Constantianae Baths is consistent with the 34 masl elevation previously suggested for the channel in this area. However, the location of the baths suggests a more southerly crossing of the valley than that suggested by Crow *et al.* (2008) and opens up the possibility that the channel crossed the saddle of the valley and followed a course on the southern flanks of Hills Two and Three (see Map 6.6).

### The Basilica cistern: endpoint of the Aqueduct of Hadrian

We know that in the late 4th century, prior to the construction of the Basilica cistern, flow in the Aqueduct of Hadrian was restricted by law to the Imperial Palace and public baths (which may have included the Zeuxippos Baths) (Cod. Just 11.42.6, trans. Frier *et al.* 2016). This makes the Basilica cistern a critical factor in determining the route followed by the Aqueduct of Hadrian. If the water supply did enter the city from the north side of the peninsula then either it ran on the slope *above* or *into* the cistern itself, since we know from Map 6.6 that the aqueduct did not run *below* the Basilica cistern.

Three options for the route of the Aqueduct of Hadrian in the vicinity of the Basilica cistern are illustrated in Figure 6.6. If the line of the aqueduct runs *above* the Basilica cistern it would push the elevation up towards 40 masl, raising the elevation along the entire line and requiring an above ground structure – an arcade or bridge – to cross the valley between Hills Three and Four (previously ruled out for want of evidence and unnecessary vulnerability).

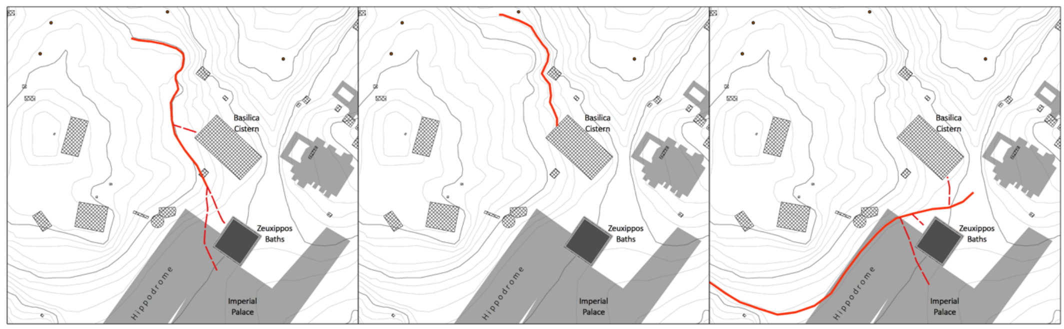


Figure 6.6: The three options for the Aqueduct of Hadrian feeding the Basilica cistern, from left to right: approaching from the north and above the cistern; approaching from the north and terminating at the cistern; and, approaching from the south.

If the Aqueduct of Hadrian ran *into* the Basilica cistern, it would have done so at about 32-36 masl. Thus, it could only have flowed out at a lower level (the Basilica cistern being about 9 m deep) which would preclude the possibility that it fed the Zeuxippos Baths or the Imperial Palace (with elevation ~30 masl), meaning that when the Basilica cistern was built it became the terminal point of the line. We know that the Zeuxippos Baths continued to operate as baths until at least 713 and the Imperial Palace continued to be occupied. If the water supply was cut off by the construction of the Basilica cistern, considerable work would be required to re-route supplies from the Aqueduct of Valens. However, this only applies if the Aqueduct of Hadrian took the northern route into the city; the southern route allows supplies to be maintained to all the relevant structures, including the Basilica cistern at a more probable elevation of 32 masl, as shown in Figure 6.6.

During the Avar siege of the city in 626, the Aqueduct of Valens was cut, preventing water from flowing until its repair in 765/6 (Theophanes *Chronicles* AM 6258 trans. Mango & Scott 1997, p. 608). That the city survived for 140 years without this major source suggests that the flow in the Aqueduct of Hadrian was accessible and capable of supplying key structures. This was not an aqueduct that had been truncated and relegated to backup status in time of severe summer drought; it was a fully functioning system that enabled the city of Constantinople to survive a major attack on its infrastructure.

It would appear that, at least in later years, the Basilica cistern was connected to the water system at its southeast edge, close to the Hagia Sophia. A sluice control connected to the Basilica cistern was reported in front of the Hagia Sophia[56] (Forchheimer & Strzygowski 1893, p. 55) and a channel was revealed during construction of the tourist exit from the cistern in the 1980s (Çeçen 1996a, p. 25-27).[57] Today, no inlets or outlets to the cistern are known. While none of this evidence is conclusive, it builds a picture of the advantages of a southern route into the city.

### Channel in the grounds of Hagia Sophia

During excavations in the west courtyard of the Hagia Sophia, remnants of the earlier Great Church were discovered, along with a street, running roughly southeast-northwest which had a large 2.2 m wide channel running beneath it (Schneider 1941, pl. 2). It is not clear if this channel could be linked to the channel described by Çeçen (see n.57) which may connect the "Hagia Sophia Distribution Centre" and the wells in the Topkapı Palace. Recent explorations of the tunnels and chambers beneath Hagia Sophia and its surroundings (Özkan Aygün 2010) have revealed a complex network of channels (including the 2.2 m

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[56] Gilles (trans. Byrd 2008, p. 101) also reports seeing an inflow to the cistern, described as a large pipe and clearly high up the cistern wall, but does not indicate the location of the inflow.

[57] Çeçen photographed the channel, described as coming from the Hagia Sophia distribution centre, and associated the same channel with two deep wells in the grounds of the Topkapı Palace (see section 6.6.1 for further discussion of the structures and the potential connections). These Ottoman structures may have been constructed around an older Byzantine-era well, as reported in Tezcan (1989, p. 241-246).

channel), although the original function of these structures remains uncertain. The channel running beneath the street in the west courtyard of Hagia Sophia is assumed by Schneider (1941, p. 3-4) and Bardill (2004, p. 27-8) to be a sewer, but if a southern route is now considered, it is feasible to identify this channel with the Aqueduct of Hadrian, flowing northwards along the north-east slope of Hill One.

### 6.3.3 The evidence of Ottoman Constantinople

#### The comparative evidence of the Ottoman System

If the Ottoman Kırkçeşme system exploits the same source and (as traces of older structures in bridges on the Kırkçeşme Aqueduct suggest) a similar route into the city, an examination of the newer system should provide insights into the older system.[58] Maps (reproduced in Çeçen 1999) that show the route the later system took within the city and identify fountains and control towers can be used to examine the water level during Ottoman times, which can serve as a proxy for the level of the Aqueduct of Hadrian.

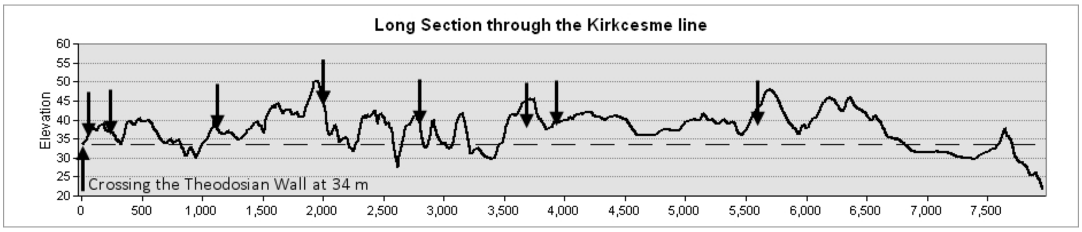

Figure 6.7: Ground profile through the Kırkçeşme line within the city, from the crossing point at the Theodosian Wall (left) towards the Topkapı (right) using a digitised version of Çeçen's 1999 map on a 3D model of the city based on contours from Müller-Wiener's 1977 map. Arrows indicate approximate locations of çeşme (fountains) that are positioned above the 34 m crossing level at the Wall.

The Ottoman system operated as a locally pressurised system, with water being driven through pipes by gravity between control towers called *suterazi*; thus, a series of inverted siphons distributed water through the city (Andréossy 1828 pl. 2, Crow 2015). This system would allow water to overcome localised obstructions and changes in level. However, as the system was still operating under gravity,

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[58] Tursun Bey, *The History of Mehmed the Conqueror;* Gilles, *De Bosporo Thracio, Libri III, 2.3,* both quoted in Crow, Bardill and Bayliss (2008, p. 242-43).

the overall water level dropped as it was moving from upstream to downstream. Fountains and other structures with a free water surface (i.e. not under pressure within a pipe) could not be at an elevation higher than the free water surface further upstream.

The maps of the Kırkçeşme system are puzzling. The crossing point near the Theodosian wall is at approximately 34 masl, and photographs (Çeçen, 1999 p. 104) indicate that the water has a free surface at this point (i.e. not under pressure), yet much of the downstream network on the Kırkçeşme line is higher than 34 masl. The longitudinal section in Figure 6.7 shows the variation in ground level along the route of the main Kırkçeşme line from the Land Walls to the east of the Topkapı Palace; several fountains along the route are higher than the established 34 m baseline, an arrangement that is physically impossible and leads us to question some of the assumptions made regarding the system. Given that much of the route within the Land Walls is above an elevation of 34 m,[59] we must conclude that the structure at the crossing of the Land Wall is either a branch off the main line or has been located on maps incorrectly. The water must arrive at a higher elevation than was previously believed. This therefore removes the constraint of assuming that the Aqueduct of Hadrian also arrived around this level, and we can progress with the assumption that it reached the city at an elevation above 34 m.

### City routes – Hill Three – northern, southern or both – the Tezgahçılar Kubbesi structure

The next question is the route taken after the channel crossed the valley between Hills Four and Three. As discussed above, the line of the Aqueduct of Hadrian was previously drawn at a low elevation (already sitting below 30 m elevation at the Hill Three/Hill Four valley) and, as a result, could only follow the northern path, taking a sinuous route around the spurs of Hills Two and Three. However, the Ottoman Kırkçeşme system, positioned significantly higher, splits at this valley, with a branch to the north and the main line to the south, to arrive at the platform between the first two hills near the middle of the

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[59] Ground-level is an imperfect proxy for pipe inverts since pipes could be buried, but the presence of fountains on or close to the Kırkçeşme route and above 34 m in elevation indicates that the pipes were running near to the surface at these points.

Hippodrome (Çeçen, 1999, Maps 30-33). The shape of Hills Two and Three makes this southern route shorter and the gradient of the slopes traversed is shallower, which from an engineering perspective would be easier to construct (compare the original route in Figure. 2.2 and the new route in Map 6.8).

The splitting point of the Ottoman Kırkçeşme system (see Map 6.7) is the Tezgahçılar Kubbesi. Sitting on the modern 40 m contour, the structure is buried up to its roof and is about 5 m deep, putting the channel invert at an elevation of 35 masl. From this structure, the Kırkçeşme system could take the northern or southern route around Hill Three. However, the Tezgahçılar Kubbesi has been identified as originally Roman,[60] with Ottoman repairs and alterations. Although adjacent to the Bozdoğan Kemeri, it is 15 m lower, indicating that this structure was not part of the Aqueduct of Valens. Thus, if the original structure is Roman, it could only be associated with the Aqueduct of Hadrian. As such, it is reasonable to assume that the Aqueduct of Hadrian was also capable of taking either a southern route, a northern route, or both.[61]

It is difficult to conclude if the Aqueduct of Hadrian split in two, like the Ottoman system, or merely crossed to the southern route. As the original town of Byzantium was not extensive and did not extend over the northern slopes of Hill Three, there would be little to justify the more complicated construction. However, this area was densely populated in the days of early Constantinople, which may have justified alterations to the existing arrangements, perhaps associated with the rebuilding of the line towards the end of the 4th century (*Cod. Theo.* 6.4.29). Two of the city's four *nymphaea* are located in Regions IV

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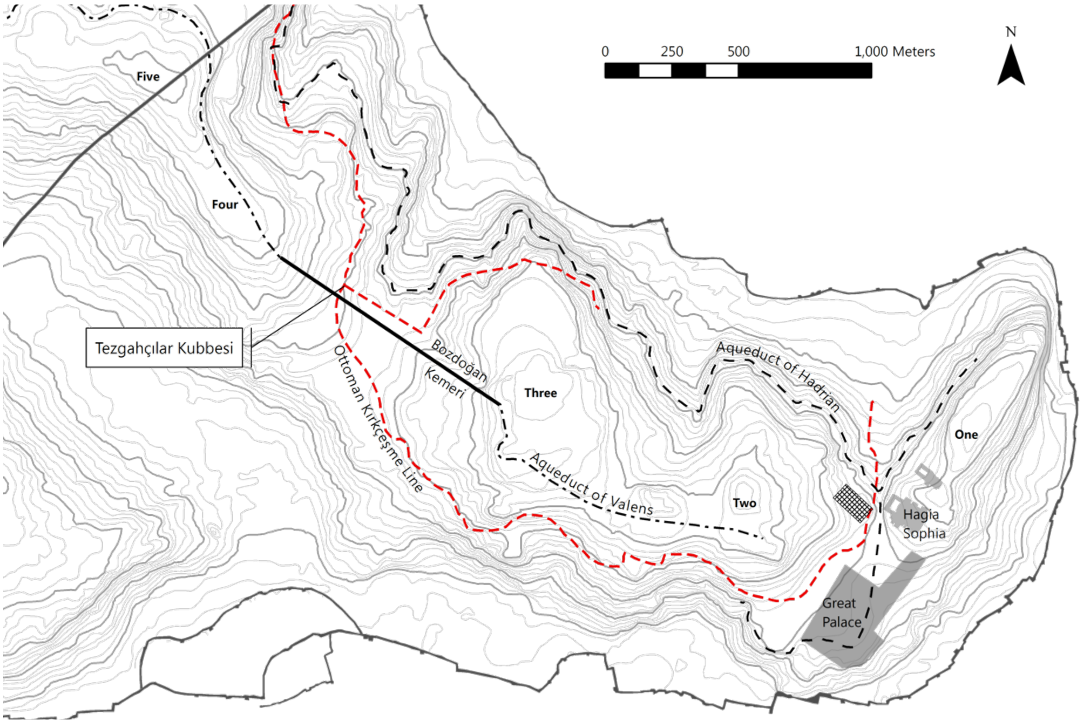
[60] Çeçen (1996a p. 215); Çeçen (1999 p. 105-6); and included in Altuğ (2013 p. 426-27) as belonging to the Early Byzantine period. Although Crow, Bardill and Bayliss (2008 p. 116) indicate that the early dating of this structure should be treated with caution, Dark & Özgümüş, (2013 p. 127 with pl. 2), identify this structure as a Byzantine cistern that has been uncovered by modern work, rather than a control structure that has been buried over time. The plan included in Altuğ (2013 p. 427), indicates an access to the structure *c.*2.5 m below the present ground-level.

[61] It is also worth noting that the northern and southern branches of the Ottoman Line are unequal; the north branch, wrapping around the steep slopes of Hill Three is relatively short. On the other hand, the south branch wraps around the southern slopes of Hill Two and Hill Three, and continues round to also supply the north slope of Hill Two, which may be an indication of the difficulty of construction on the north slope.

and V (on the northern slopes of Hill Two), and could perhaps have been supplied by the Aqueduct of Hadrian.



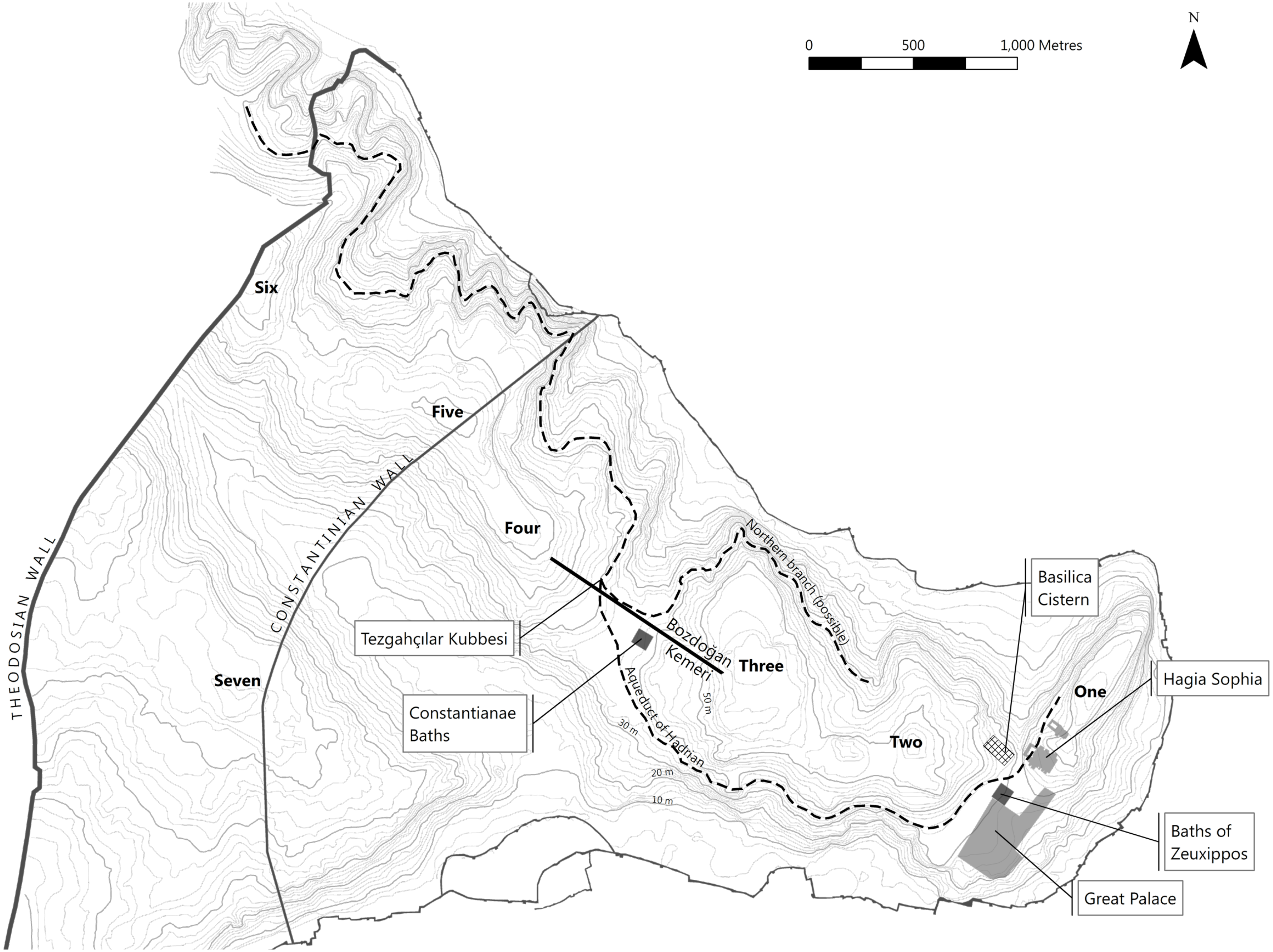
Map 6.7: The Ottoman Kırkçeşme route and the Aqueduct of Valens at Hills Three and Four, and the location of the Tezgahçılar Kubbesi. The Ottoman Kırkçeşme line is after Çeçen 1999 maps 30-33; the Aqueduct of Hadrian and Aqueduct of Valens lines shown are from Crow, Bardill and Bayliss 2008 maps 12-15.

### 6.3.4 Proposed route of the Aqueduct of Hadrian

- At the platform area between Hills One and Two, the Aqueduct of Hadrian was high enough to feed the Zeuxippos Baths.
- The location of the Basilica cistern and the structures known to be fed by the Aqueduct of Hadrian make a southern route into the city more favourable.
- At the valley between Hills Three and Four, the Aqueduct of Hadrian was at a level sufficient to cross the saddle of the valley; this opens up the possibility of a southern route into the city.

- The differences in topography of the north and south slopes of Hills Two and Three make a southern route into the city shorter and more straightforward to construct.
- The line is probably higher than previously thought when crossing the Land Walls, as the Ottoman system levels previously used as a proxy are inconsistent.

As shown in Map 6.8, the route proposed for the Aqueduct of Hadrian crosses the Theodosian Wall at a level of about 39 masl. At the valley between Hills Three and Four, the line hugs the flank of Hill Four, passing through the structure later called Tezgahçılar Kubbesi. From here, the channel may branch, with the main branch being the southern one which traverses the valley and follows the contours on the southern flanks of Hills Two and Three, bringing water to the head of the north-facing valley around the harbour. When the town became Constantinople, this southern branch continued to supply many of the key sites in this part of the city, and a northern branch may have been added, extending from Tezgahçılar Kubbesi into the densely populated flanks of Hill Three.



Map 6.8: Suggested route of the Aqueduct of Hadrian within the city, with possible northern branch from the Tezgahçılar Kubbesi.

## 6.4 The route of the Aqueduct of Valens

The Aqueduct of Valens was built in two phases during the early days of the new city when not only the population was increasing but also the area occupied by the city was expanding. This expansion generally moved upwards and outwards from the old city of Byzantium, incorporating a number of hills that could not be served by the Aqueduct of Hadrian. Maximising both the elevation of the channel and the area served would have driven the choice of route for the new line. The engineers would also aim for a route that minimised the length of the channel and the complexity of construction. The Aqueduct of Valens was constructed before the cisterns associated with it: the aqueduct arrived in the city in 373 and the first major cistern, the Aetius Cistern, was constructed in 421 (about the same time as the second phase of the Aqueduct of Valens is believed to have been under construction). We do not know whether the cisterns were planned in advance and influenced the aqueduct route but, as they had to be connected to one of the aqueducts in order to be filled, it is reasonable to assume some degree of proximity between cistern and aqueduct. However, the siting of cisterns would have been influenced by a number of other factors, including available space, topography and downstream connections, so caution should be exercised in relying on the location of a cistern to define the location of the aqueduct.

### Evidence for the route

Although there is more physical evidence that may be associated with the Aqueduct of Valens than there is with the Aqueduct of Hadrian, the interpretation of some of this evidence is difficult. The most obvious, still-visible, evidence is the aqueduct bridge crossing the valley between Hills Three and Four. Now called Bozdoğan Kemeri, it is a clear indication the aqueduct followed a route along the high ridge of hills within the city. Once thought to carry the Aqueduct of Hadrian, the bridge has been confirmed as belonging to the Aqueduct of Valens.[62] Although the ends of the bridge have been lost, we have its alignment and channel elevation (57 m at the western (upstream) end –

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[62] Following Dalman (1933), Mango (1985, p. 20) suggested attribution to Hadrian, but was more cautious in 1995 (p. 12.) See Crow, Bardill and Bayliss (2008, p. 13-14) for dating and attribution.

measured at arch 1 by Dalman, quoted in Crow, Bardill and Bayliss (2008, p. 120)). The other physical evidence is scarcer and less conclusive. A recently discovered channel upstream of Bozdoğan Kemeri might be associated with the aqueduct. A number of brick channels, stone channels and marble pipes observed along the modern Ordu Caddesi and Divan Yolu Caddesi align closely to the ancient main street of the city, the Mese, but these structures have not been subject to detailed study, some being identified as water channels, some as drainage structures.

### 6.4.1 Upstream of the Bozdoğan Kemeri

#### Channel in Baş Müezzin Sokak

A large vaulted brick channel, (Figure 6.8) running perpendicular to Baş Müezzin street is a strong candidate for the Aqueduct of Valens upstream of Bozdoğan Kemeri.[63] The channel is at the highest point of the street, close to where it crosses Boyacı Kapısı Street. At just over 2 m wide and about 2.5 m tall, the brick channel was capable of carrying high flows. Hydraulic mortar (which would be strong evidence of the channel being part of the aqueduct) is not recorded, but the channel's position on top of the ridge effectively eliminates the possibility of the structure being a drain. The location indicates that the aqueduct would follow a route on the peak of the ridge or its southern side, rather than the northern side as previously shown (see Figure 2.2 in chapter 2). The northern route around Hill Five is longer than the southern, but it does pass alongside the Aspar Cistern. It is interesting to note that the Ottoman Halkalı system takes a similar route, across the southern side of Hill Five, as shown in Figure 6.9.[64] I propose that the main channel took the southern route around Hill Five, and that a branch was constructed at the time of the construction of the Aspar. The ground level at the point the channel was found

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[63] Baş Müezzin Sokak lies northwest of the Fatih Camii, the site of the Holy Apostles church. I am grateful to Kerim Altuğ for informing the project of this discovery, the details of which (the photograph included as Figure 6.8 and a sketch of the site) are in the Istanbul Municipal Archive.

[64] It is possible that the Ottomans were using a route already established towards the end of the Byzantine period in Constantinople. Clavijo reports water flowing over the Bozdoğan Kemeri in the 15th century, after the long-distance aqueducts were reported to have been damaged beyond repair (Clavijo, *trans.* Le Strange 2005 p. 88 and Kinnamos, *Deeds of John and Manuel Comnenus* 6.8 (trans Brand 1976, p. 205-206) for report of long distance aqueduct failing in the 12th century).

is high, approximately 67.5 masl. From Figure 6.8, it is apparent that the channel is positioned just beneath the road surface; thus, we estimate the channel invert level at 64-64.5 masl. One kilometre upstream the channel must pass the saddle between Hills Six and Five, adjacent to the Aetius Cistern. As the modern ground level at this saddle is about 62-63 masl, the channel must have crossed on a raised substructure or used an inverted siphon.

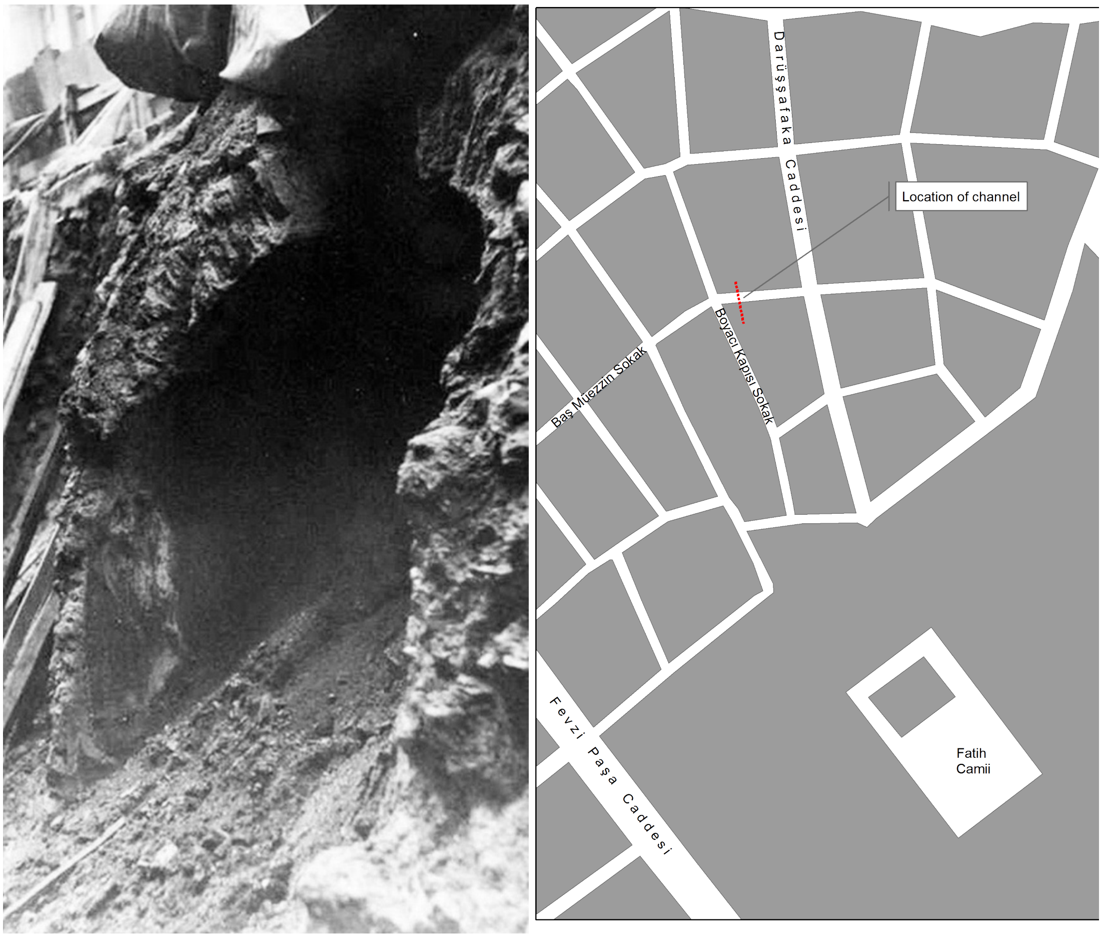

Figure 6.8: Channel found beneath Baş Müezzin Street (Istanbul Municipal Authority, courtesy of Kerim Altuğ)

Downstream from the channel in Baş Müezzin Sokak the land drops to the Bozdoğan Kemeri, requiring the channel to drop some 7 m in elevation over a length of 500 m – a rapid drop which could create undesirable flow conditions particularly where the gradient flattens to cross the bridge. To avoid a potentially damaging hydraulic jump, the channel may have incorporated drop structures similar to those studied by Chanson (2000) or, potentially,

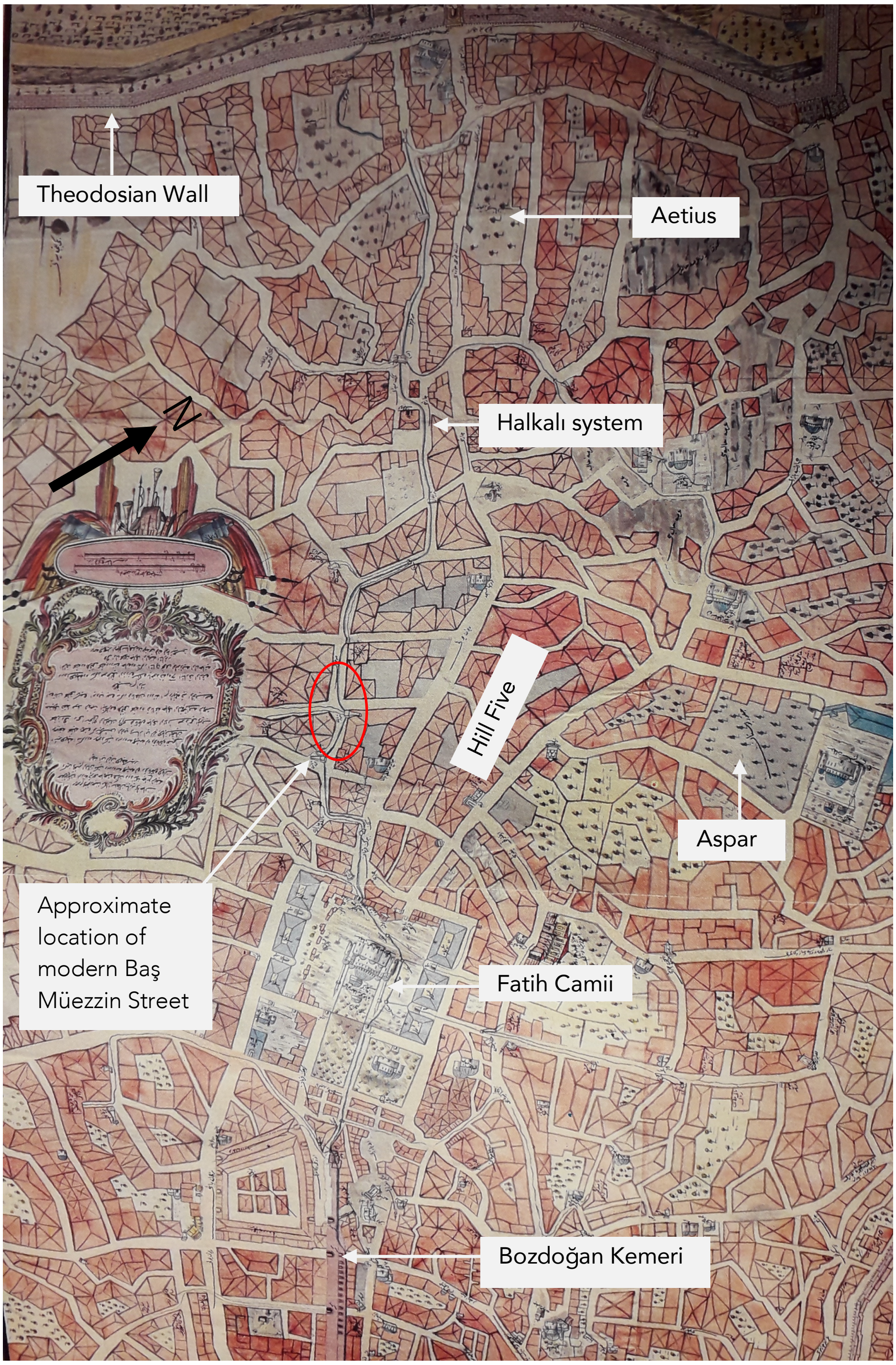

Figure 6.9: Extract of the Ottoman Bayezit Water Supply System (1815-17), Çeçen (1991, Map 7), labels added by author.

used the sizeable cistern (D5/5 in Appendix B) (38 m x 26 m) on the north flank of Fatih Camii[65] as a settling basin, entering at a relatively high gradient but

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[65] The partially collapsed cistern measures at least 38 m x 26 m. It has some evidence of an inflow channel in one corner: Altuğ (2013, cistern 137, p 414-15).

exiting at a gradient and level suitable for crossing the bridge. The large volume of water could provide a buffer to allow the transition from a relatively steep channel to a relatively shallow one.

## 6.4.2 Evidence along the Mese

#### Sewers, storm drains or water channels: resolving the evidence near the Mese

Although vaulted channels and pipes ran below the line of the Mese, the ancient main street of Constantinople, their exact purpose is not immediately clear. Evidence of the pipes and channels found between Forum Tauri (Bayezit) and the Milyon are outlined below and their locations are illustrated in Map 6.9.

| | |
|---|---|
| Forum Tauri | 1. Two parallel channels running approximately east-west through the Arch of Theodosius, which were described as possible water channels (Casson 1929, p. 40). These channels are in close proximity to two further discoveries: 200 m east of the Theodosian Arch three parallel channels (1.6 m wide) were uncovered; between these two excavations, a third found a single channel (Müller-Wiener 1977, p. 261 and fig 294).[66] |
| Forum Tauri | 2. Four small channels running approximately north-south excavated slightly north of the arch (Naumann 1976). These are not of a size to be associated with the channels crossing Bozdoğan Kemeri (the largest is about 0.5 m wide), but could possibly be interpreted as drains that discharge into the larger channels beneath the Mese. The channels were not all contemporary – some appear to be later replacements which cut across the line of older channels, providing some rare evidence of maintenance or renewal of part of the water or drainage system. |

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[66] The single channel is unmarked on the diagram but noted as D in the caption, midway between A and E.

| | |
|---|---|
| Tiyatro Aralığı Sokak | 3. Two parallel channels and two parallel pipes, offset to the south of the line established by the channels at Forum Tauri in an excavation in Tiyatro Aralığı Sokak. An image of the excavation (Altuğ 2013, p. 42 fig 3.15) shows large marble pipes, described as running in an east-west direction. The two-part photo also shows two parallel channels (size not recorded but, from the photograph, considerable and potentially similar to those seen at the Forum of Constantine) which could also be associated with the water supply. To judge from the photograph, the pipes are similar to those now found in the grounds of Hagia Sophia (see Fig 2.3, with approximate diameter of 300 mm); the relationship between pipes and channels is not clear. |
| Near Kara Mustafa Paşa Medrese – east of Tiyatro Aralığı Sokak | 4. Large marble pipes running in two (possibly more) parallel lines (Müller-Wiener 1977, p. 268-9 figs. 303 and 305). The direction of the pipes is not clear from the photograph, it appears to be roughly parallel with the Mese. There are no indications of channels in this excavation, although it is not clear whether it extended across the full width of the road. |
| Forum of Constantine | 5. Two sets of two parallel vaulted channels discovered north (approx. 1.8 m wide and 2 m high) and south (approx. 1.6 m wide and 2.5 m high) of the Column of Constantine. One set of channels (running to the north of the column of Constantine) is described as constructed in brick, the other in stone (Mamboury, 1936, p 254, see also Figure 6.10 for a sketch plan of the site). |
| Milyon | 6. A single vaulted channel with a branch going in (or coming from) the direction of the Hippodrome (Müller- |

Wiener 1977, p. 216 fig. 245). The connection detail between the branch and main channel shown in Müller-Wiener's fig. 245 is noteworthy. The narrowing of the channel at the point of connection may have been to support a control mechanism (such as a lifting gate). If flow was from the branch into the main channel (as would be the case for a drain), the sharp corner would likely see a build-up of material over time and would need regular cleaning.

Various points along the Mese

7. Vaulted structures from which bricks with brickstamps were removed beneath the eastern end of the Mese, between Atık Ali Paşa Mosque and Firuz Ağa Mosque (Bardill 2004, p. 77-8 reporting from the notes of Mamboury).

How can these pieces of evidence be related to drainage or water supply infrastructure? Drainage and water supply can both be gravity-fed, but the design features differ. As smaller channels feed into progressively larger ones, drainage accumulates flow like a river system, whereas water supply distributes flow from larger into smaller channels. Ideal flow conditions also differ. In water supply, maximising elevation is crucial, with the result that shallow gradients and slow velocities are normal. Drainage requires steeper gradients and faster velocities for the rapid removal of wastewater to prevent deposition and odour.

The channels discovered at the Forum of Constantine (no. 5) and under the Arch of Theodosius (no. 1) were at approximately the same elevation. If they were connected, the gradient between them was extremely shallow.[67] These poor flow conditions, exacerbated by the parallel channels being interconnected (effectively creating one very wide channel), make it unlikely that they were sewers carrying human waste. Both the flat gradient of the channels – if they

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[67] Mamboury (1936, p. 253) assumed that the channels were drains running continuously from the Augusteon to the Lycus near the Forum Bovis and used this as a proxy for the line of the Mese. Because of the change in elevation, it is most likely that, if it was a sewer, the line was not continuous but actually sloped in two directions, draining to both the east and the west, with the split located somewhere between the Fora of Constantine and Tauri.

were connected along the Mese – and the interpretation of the double channel as redundancy (allowing access for repair whilst maintaining an essential flow of water) support the hypothesis that the channels form part of the water supply. On the other hand, the position and arrangement of the channels suggest they are not water supply infrastructure: they do not take the highest route available; they flow beneath the Mese, making supply to street level difficult; and the connection with Bozdoğan Kemeri entails a 90° bend at the end of the bridge and again at the Arch of Theodosius, a needlessly complex arrangement.

The details included in Mamboury's sketch (replicated in Figure 6.10 below) of the Forum of Constantine (Bardill, 1997, p. 72 fig. 3) do little to clarify the situation. The southern pair of channels (no. 5.2 in Map 6.9 and identified by Mamboury as 5th century) are clearly shown as connected just to the east of the column, which would worsen flow conditions for drainage. On the other hand, a drain inlet intruding into the southernmost channel is noted someway further east, midway between Peykhane Sokak and Boyacı Ahmet Sokak. This suggests that the channels were drains but the fact that only a single inflow is present along a length of approximately 150 m (particularly when much of that length was known to be a paved forum) leads me to suggest that the drainage connection might be a later addition that took advantage of the (by then disused) channel. The branch channel following the line of the Vezirhan Caddesi is also ambiguous – there is no room to pass above the so-called 8th century parallel channels (no 5.1 on Map 6.9), so either this branch passes beneath, suggesting it is extracting something from the so-called 5th century parallel channels, or the branch passes through the so-called 8th century channels and is a later addition. The fact that it follows the modern street line tends to support the channel being a more recent work and so does not provide evidence either way as to the original use of the channels.

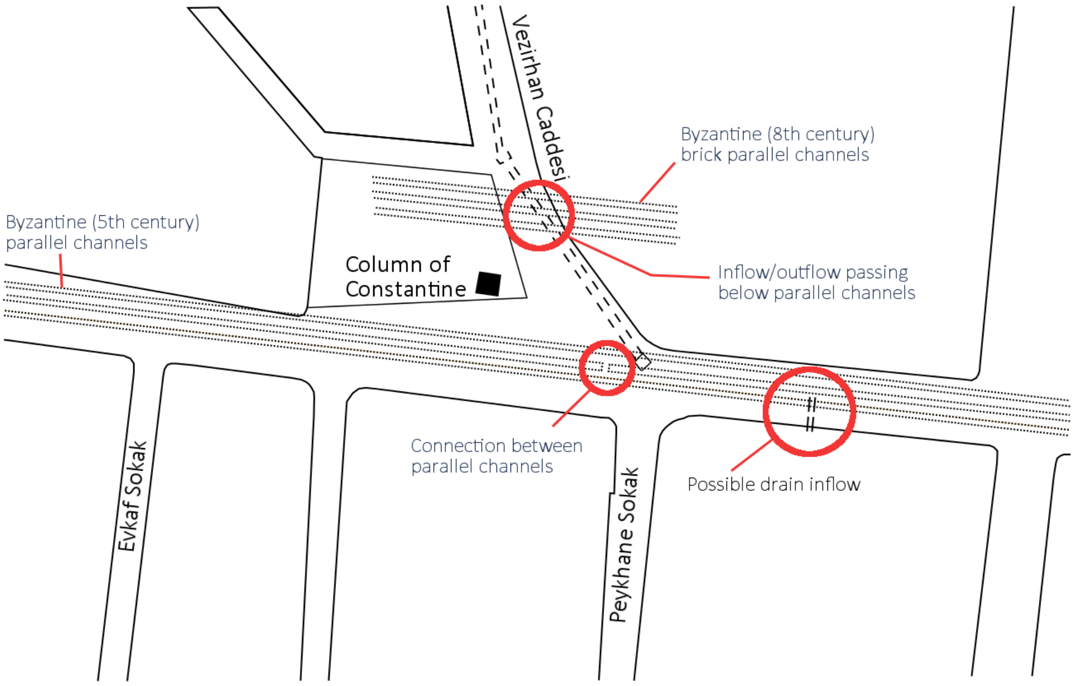

Figure 6.10: Plan of discoveries made near the Column of Constantine, after Mamboury (Bardill 1997 Fig 3), adapted to show the water related discoveries. The dating of the channels is by Mamboury.

We can be more certain about the pipes found at Kara Mustafa Paşa Medrese (no. 4). Their location, slightly west of the lowest point of the ridge between Hills Two and Three, could indicate that they formed a flat inverted siphon, using pressure flow either to overcome the drop in elevation or to pass through an area with insufficient ground-cover to incorporate a channel. This would be unnecessarily complicated and costly[68] for a storm drain, particularly when there is a clear option to drain down the slope towards the sea. However, as Roman engineering situates a water supply channel to minimise loss of elevation, additional costs for pipes and siphons are justifiable. Thus, we can identify the pipe finds at Tiyatro Aralığı Sokak (no. 3) and west of Kara Mustafa Paşa Medrese (no. 4) as part of the water supply.

The channels beneath the Mese (nos. 1, 5 and 7) are not sewers and are unlikely to be water supply. While their generous proportions are consistent with storm drains, the street collection and guttering (of which there is very little evidence)

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[68] This forms part of Riley Snyder's work on the project *Engineering the water supply of Byzantine Constantinople*, in which manpower rates from Pegoretti (1864) are compared for equivalent lengths of hollowed-out pipe and masonry channel.

would need to be large, regular and efficient for the channels to be used at capacity. The catchment area of the drains would be relatively small; as they run parallel with and close to the ridge there is not much land above the channel to drain into them.

The solution is far from certain but it offers an arrangement of both water supply and drainage structures that reconciles the available evidence. The channels referenced as nos. 1 and 7 and the southern portion of no. 5 are assumed to be drains (Map 6.9). The channel at no. 1 flows west into the Lycus or Harbour of Theodosius while the channels at nos. 5 and 7 flow east towards the Augusteon, discharging around the Prosphorion Harbour. The Valens Line is expected to maintain a position on the high ground north of the Mese, distributing water to the Cistern of Philoxenus[69] before doubling back along the Mese, initially in the channels at the north portion of no. 5, then at no. 4 in pipes whilst crossing under the road, and discharging into channels at no. 3 to feed the cisterns on the south side of Forum Tauri.

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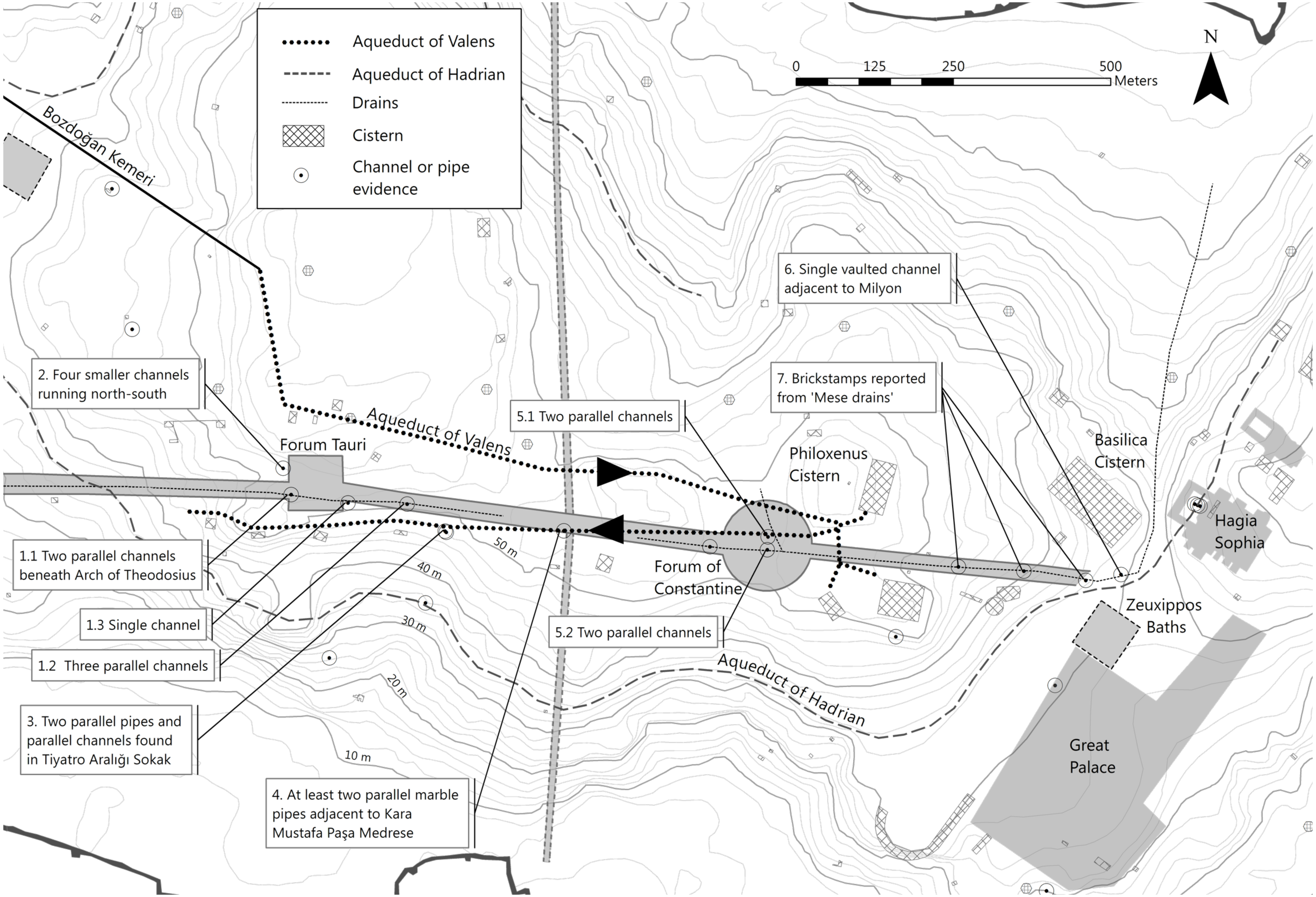
[69] The cistern on Bab-ı-Ali street, which is identified as the Cistern of Philoxenus by Bardill (1997, p. 69-75).



Map 6.9: Detail of channel and pipe evidence in the vicinity of the Mese and a possible interpretation of that evidence as a combination of storm drains and water supply infrastructure.

### 6.4.3 The end of the Aqueduct of Valens

The end point of the aqueduct provides an indication of the full extent of the water supply network reliant on it. As the Aqueduct of Valens is the high-level water provider in the city, it is logical to initially assume that the aqueduct followed the line of high ground that extends from Hill Six at the Theodosian Wall to Hill Two, near the heart of the old city. The channel may have gone no further than Hill Two, terminating in either the Philoxenus cistern, Binbirdirek cistern or, possibly, both of them. Based on the construction dates for these cisterns (early 5th and 6th century respectively) Crow *et al.* (2008, p. 123) suggest that the terminal point may have initially been further out, at the nymphaeum near Forum Tauri, although they note that there were structures on and around Hill Two that would have needed a water supply prior to the construction of the Binbirdirek and Philoxenus cisterns.

Both the Philoxenus and Binbirdirek cisterns are unusually deep: the Binbirdirek has double height columns of about 14 m and excavations behind the remaining wall of the Philoxenus on Bab-ı-Ali Street reached a depth of 14 m without discovering the floor of the cistern (Altuğ 2013, p. 258-9). Initially, these deeper cisterns, which maximise storage volume, appear to be strong evidence that the aqueduct terminated here. Water reaching the end of the aqueduct that cannot be stored would have to be spilled, so larger cisterns would be a good solution for minimising waste. However, the cisterns would only be able to accept large quantities of water if the amount of water extracted was similarly large. The high population density nearby (discussed in Section 5.4.4) would provide high demand for extraction, however, as well as the need for water, it would also need to be possible to extract water in large quantities. Consideration must be given to how water held within the deep cisterns was accessed. Lifting water out of the cistern, either by hand or by lifting device, would tend to limit the rate of extraction, which would limit the space available for storing water if the cisterns acted as the terminal points of the aqueduct. If the water must be lifted out to the surface level, the storage is not particularly convenient and the large size of the cistern offers little advantage (except in the case of prolonged drought). The alternative to lifting water is extracting at a low level, tunnelling into the hillside to get access. The base of both cisterns was approximately 38 masl, and despite the steepness of the surrounding topography, a considerable horizontal distance from ground at this elevation. The cisterns may have served as oversized *castella aquae*, distributing water to the lower portions (below 38 masl) of the north and south slopes of Hill Two. No evidence of low level channels emerging from the hill side has been found, but given the size of these cisterns it is the most logical method of extraction. On further consideration, the large size of the cisterns does not necessarily indicate the terminal point of the aqueduct but does suggest that the flow reaching this point was quite high and, therefore, could be capable of continuing on to provide supply to other areas around Hill One. For water to continue on from Hill Two, it either needed to be carried on a bridge or arcade,[70] or drop level significantly, into the Aqueduct of Hadrian. The base levels of the Philoxenus and Binbirdirek cisterns are above the level of the Aqueduct of Hadrian, so they could potentially be used to transfer the water into the lower channel. The possibility of the Aqueduct of Valens continuing on to feed Hill One is discussed more fully in section 6.6.1, which concludes that the cisterns of Hill One were likely to be fed by water from the Aqueduct of Valens.

### 6.4.4 Proposed route of the Aqueduct of Valens

The route of the Aqueduct of Valens remains far from certain. Upstream of the Bozdoğan Kemeri, the channel appears to have run at a higher elevation and further to the south than previously proposed. Based on the discovery of a large channel in Baş Müezzin Sokak, the main route for the Valens Line is likely to have been on the south side of Hill Five, with a branch to feed the Aspar Cistern added when the cistern was constructed in 459. This finding also suggests that the channel was above ground for a brief stretch between Hill Six and Hill Five, adjacent to the Aetius cistern. Downstream of the Bozdoğan Kemeri, the channel turned south and then east to run parallel with the Mese but probably not beneath it, rather taking a route on the slightly higher ground to the north of the road, which would allow the main street to be supplied with running

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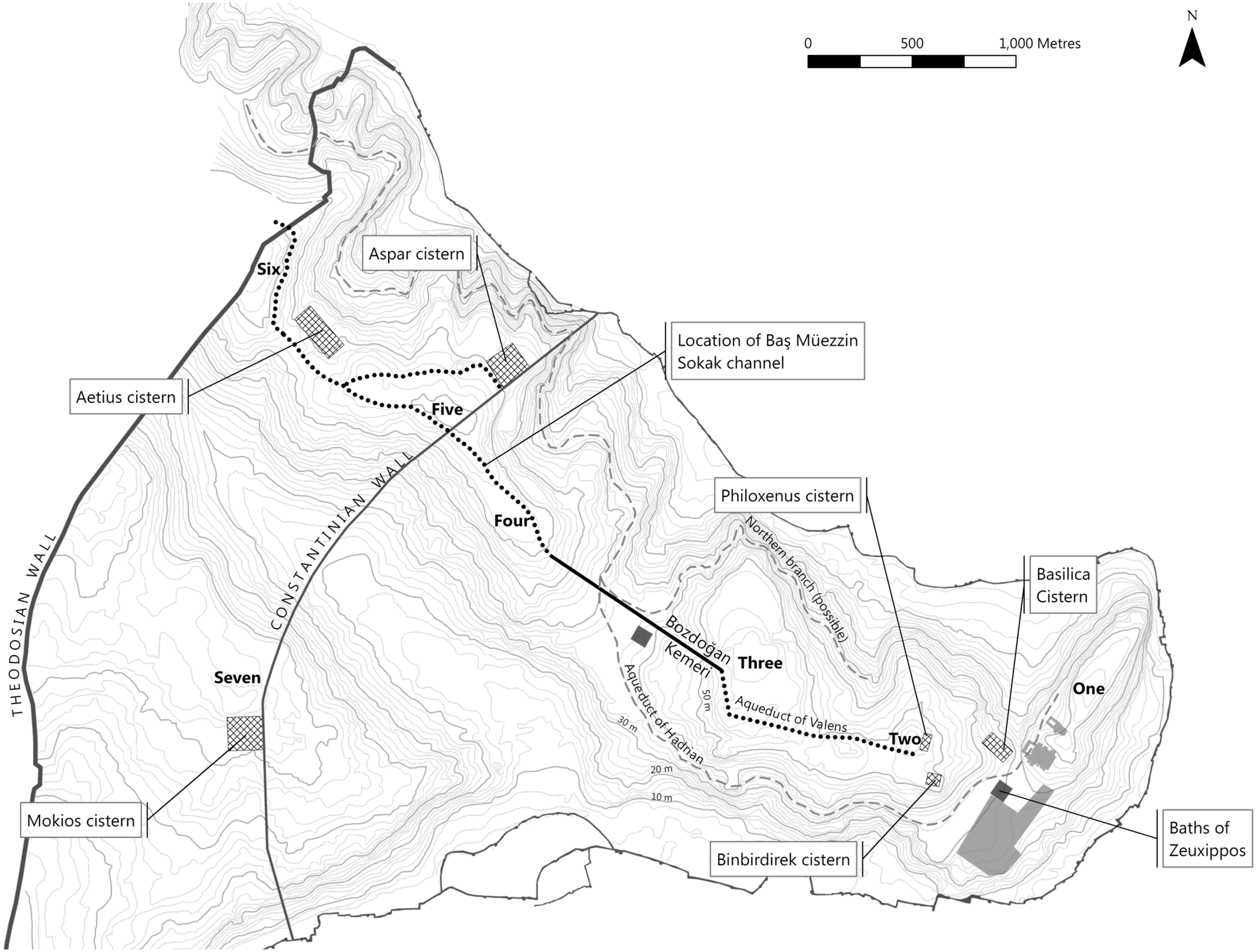
[70] This option is usually discounted as there is no mention of a bridge here in historical texts (see discussion in Crow *et al.* 2008, p. 124) however it is possible that the channel was integrated into existing architecture and so would be less noteworthy – this is the case in Rome where stretches of aqueducts were carried on top of city walls.

water. The large stone pipes found midway between the Forum of Constantine and the Forum Tauri are almost certainly associated with the water supply and suggest that the main channel doubled back along the Mese to provide water to structures on the south of the road. In Map 6.10, the Valens Line enters the city on the north slope of Hill Six at around 65 masl, taking the southern route around Hill Five to the bridge between Hills Four and Three. The line follows the highest ground towards Hill Two. In Map 6.9 the details around the Mese are shown in greater detail. It is uncertain where the Aqueduct of Valens terminated, but the Philoxenus and Binbirdirek cisterns may have acted as *castella,* serving the north and south slopes of Hill Two respectively with flow continuing on to serve the cisterns on Hill One.



Map 6.10: Suggested route of the main Aqueduct of Valens line

## 6.5 Control mechanisms

With increasing complexity comes greater need for systems of control. In Constantinople, control was not just about directing water to different locations. Decisions had to be made about when, where and how much water was stored. Considering more deeply, this control system implies a network of information was also necessary to allow informed decision making to occur. The consequences of poor decision making are quite severe: if too much water is diverted into the first cisterns in the network, an insufficient amount may reach the heart of the city at the end of the aqueducts, but if more water than is needed (or can be stored) is passed forward to the end of the aqueducts, excess water will be lost through spillage into the drainage system. The smaller the gap between total inflow and total demand, the more critical decision-making becomes.

Mechanisms would be required both to direct water into cisterns and also to regulate the flow leaving cisterns. Broadly, there are two ways of extracting water from a cistern: by lifting it to the top, or releasing it at a level lower than the water level.

In Constantinople, the only control mechanisms we have evidence of are related to cisterns, rather than aqueducts, but they do indicate the level of sophistication that control mechanisms could achieve.

### 6.5.1 Aspar Control mechanisms

The Aspar cistern, the third largest cistern in the city, has evidence of two separate control mechanisms, both believed to be associated with extracting water from the cistern. The first is located outside, approximately 15 m from the northeast wall of the cistern. The second, partially ruined, is a later addition and sits within the cistern, close to the northern corner.

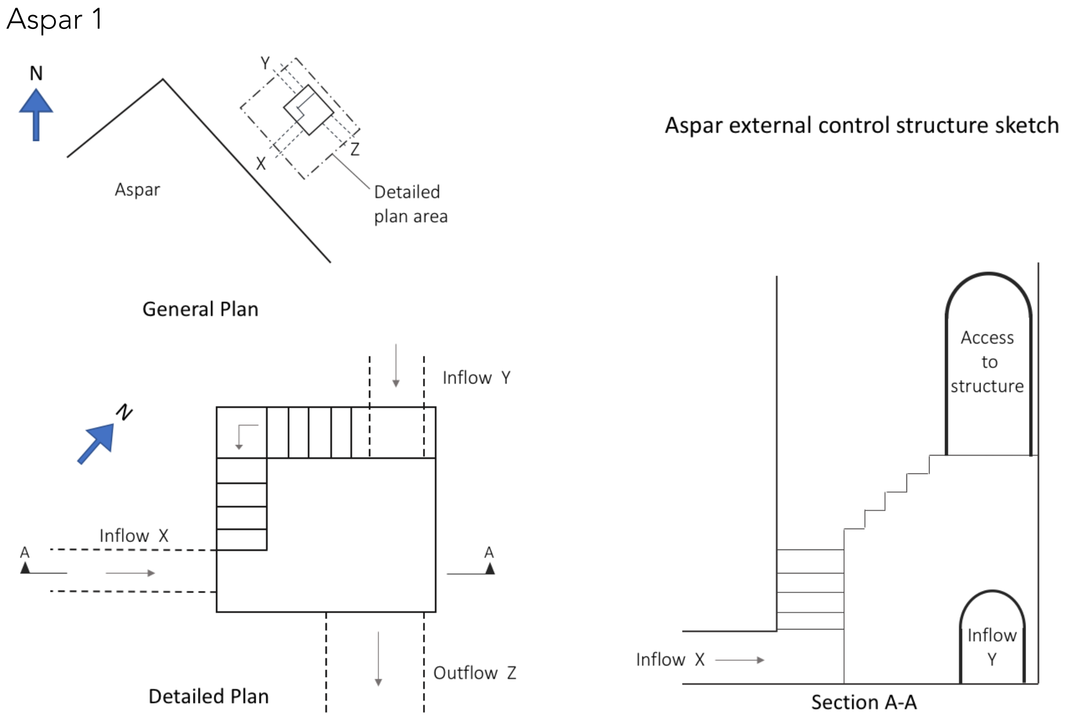


Figure 6.11: Sketches of the Aspar 1 control structure (see Figure 3.2 for a photograph of the same structure). Adapted from Sav (2010).

This structure was recently uncovered and appears to show a channel (Y to Z in Figure 6.11) running in parallel to the northeast side of Aspar and a smaller channel (X) which appears to connect with Aspar, through which additional flow could be added to the first channel. Two key design features (marked in Figure 6.11) should be noted – first that the channel assumed to be the outflow (Z) is the largest of the three channels which suggests a large increase in flow was anticipated; and second that the structure is designed for man-access: a high-level doorway provides access to a stairway that descends to the level of the top of the channel believed to be from Aspar (X). This access is possibly for operation of some manner of control mechanism associated with that channel. It was only possible to observe this structure from above, so it is not clear whether there were stone slots that once supported a gate (the structure is now overgrown and partially filled with rubbish). This structure may be evidence of infrastructure associated with moving water from the largest cisterns into the Aqueduct of Hadrian (see Section 6.2.3).

### Aspar 2

Figure 6.12: The remains of the Aspar internal tower showing an opening (left) and the blocked up opening in the dome (centre) photo: K Ward.

The second structure is more enigmatic, as there are only partial remains. It appears to be a circular tower with possibly multiple openings from the cistern at different levels and on the land side a now bricked up access in the curve of the domed roof which would be at or close to surface level. A photograph of the remains is shown in Figure 6.12. It seems that this tower was made in order to control the extraction of water, either by being a permitted location for removing water manually or by housing a lifting mechanism. Putlog holes remain which may either be left over from the construction phase or the evidence of a wooden framework that supported a mechanical lifting device. Çeçen conducted an excavation of the base of the tower area in the early 1990s (pers. comm. Kerim Altuğ) but did not find any connections or channels. The lack of low level inlets/outlets strengthens the argument that the tower was related to lifting water out to the surface rather than for controlling a low-level outflow.

Given the large size of the cistern a mechanical lifting device seems likely but even a mechanical device would be limited in its output relative to the total volume in the cistern. Therefore, it is unlikely that this was the only access point for water in the cistern, it must have operated in conjunction with others, including, perhaps, the Aspar 1 structure described above.

### 6.5.2 Fildamı control mechanisms

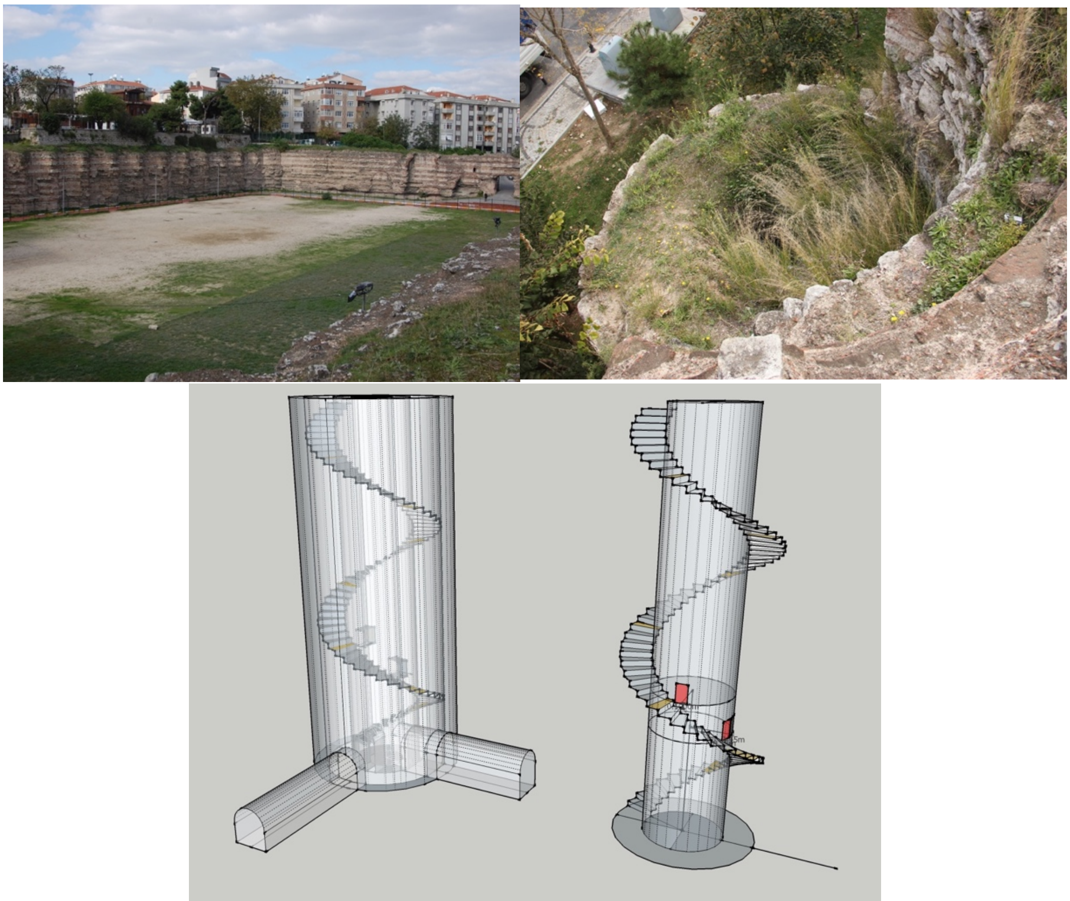


Figure 6.13: Fildamı cistern details. Cistern interior (left). Remains of control tower from above (right) and sketch (F Ruggeri) of the Fildamı tower.

The Fildamı is a large open-air cistern that is located outside the walls of the city. The construction date is uncertain but probably after the 6th century (Bardill 2004, p. 39). It is associated with a muster point for the Imperial army and is in proximity to the Hebdomon palace. The inflow arrangements for the cistern are not clear but it may have drawn on water from the nearby area of the Halkalı springs. There are three openings on the end walls (two at the south end, one on the north, visible in Figure 6.13) positioned at a relatively high level above a series of arches that would likely have supported a staircase providing access down to the water level. The function of these openings is not clear.

There is another mechanism, more clearly associated with the outflow – a tower connected to the outside wall in the southeast corner. It is located in one of the semi-circular niches minimising the distance between the tower and the inside of the cistern. Previously (in the early 2000s) the ground level within the cistern was lower and the channel connecting the cistern and the tower was visible. At this time, the tower was partially investigated by Professor Paulo Bono, and his findings presented in Crow *et al.* (2008, p. 135-7, Figs 6.7 & 6.8). This work plus my own observations from visits to the cistern under the Leverhulme project are shown in Figure 6.13. This tower is formed of two concentric circular walls with a spiral staircase between them. The cistern connects through a channel to the outer space in the tower (that also contains the staircase). An outflow channel connects to the inner space and leads roughly southwards. There are a number of openings – two, possibly three – connecting the outer and inner spaces. These openings are at different levels and appear to be positioned with reference to the spiral staircase. The water level in the outer space would match the water level in the cistern and the spiral staircase provides access to the openings (practically, only the opening closest to the water level would be accessible and therefore openable). This arrangement, opening subsequent apertures as the water level dropped in the cistern would control the outflow by allowing only a limited range of head to drive water into the inner space and through the outlet channel.

### 6.5.3 Comparative evidence of control mechanisms

Although in Constantinople there is little evidence of control mechanisms associated with cisterns, and none with aqueducts, examples of both types of control mechanisms are found elsewhere.

In Carthage (see section 3.3.3), multiple pipes with taps controlled outflow from cisterns and there was evidence of sluice-gate controlled offtakes from a major aqueduct branch (Vernaz 1887), as well as a *castellum aquae* type structure close to the point the aqueduct entered the city (Wilson 1998, 85-6). Ephesus (see section 3.3.2) appears to rely on more passive means of control, with most of the water supply that has been uncovered using pipes of different sizes extracting water from *castella aquae* tanks. In urban Pompeii, distribution is controlled by pipes connected to water towers and the distribution basin in the *castellum aquae* at the entrance to the city is also well preserved. It splits incoming flow into three channels in a purpose-built chamber. Each channel has slots carved into the sides which would have held a vertically sliding gate that could be adjusted to actively control the amount of water passing forward (Schram 2014).

Evidence of similar gates – typically it is the holding slots in channel walls that remain (see Figure 6.14) – has been found across the Roman empire, in locations that enable water to be either directed down a particular route or regulated to a particular quantity (Schram 2014). This type of technology is still seen in a modern setting, where it is typically used to control flows in open channel irrigation systems. These systems open and close gates on an established schedule to give each farmer access to water in turn for a certain number of hours. There is evidence of similar arrangements in Roman times for areas with irrigation demands – inscriptions found close to Rome detail the right to draw water for named people at certain hours from an aqueduct and there is a similar inscription for estates in Lamasba in modern Algeria (CIL 6.1261, Schram 2014 and CIL 8.18584, Wilson 2008, p. 310). It is not so big a leap to imagine a similar arrangement in Constantinople, with water being distributed to cisterns, rather than farms.

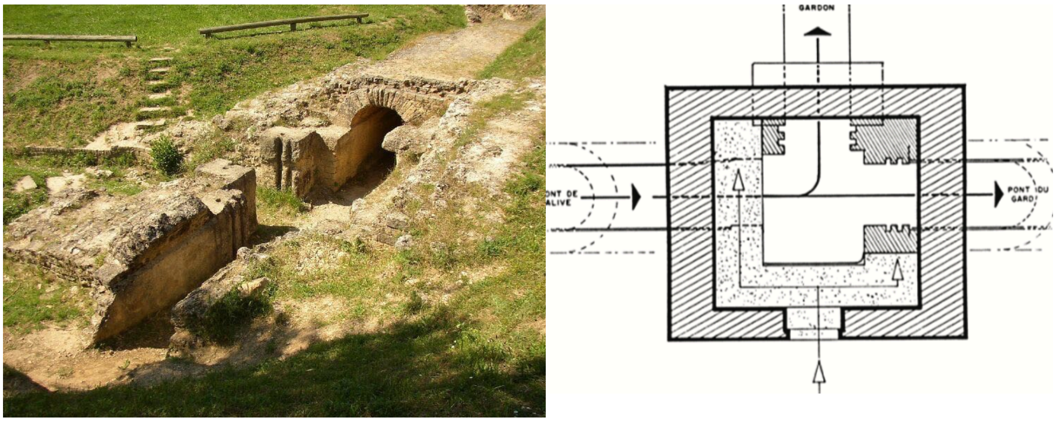


Figure 6.14: Regulation basins on the Nimes aqueduct in France. Diagram Fabre *et al.* 1991, p. 77. Photo © Schram, Passchier & van Opstal (www.romanaqueducts.info)

## 6.6 Proposed Network

The cisterns and aqueduct lines form the focus of much of this chapter but the connections between them are equally important. There is scant clear evidence of the wider network that connected everything together, though the observations by Casson *et al.* (1928, p. 25-6 and Plan II) of multiple channels and pipes crossing beneath the Hippodrome and by Özkan Aygün (2010) of the channels beneath and around the Hagia Sophia show that there was a complex unseen network beneath the city. The recent excavation of a Byzantine street beneath Büyük Reşitpaşa Road as part of the Vezneciler Metro station revealed multiple terracotta pipes running in parallel beneath the road surface (see Figure 6.15 and location noted in Map 2.5). These pipes are of a much smaller diameter than the stone pipes found beneath the Mese (see Section 6.4.2) and are probably feeding fountains, private dwellings and, possibly, smaller cisterns.

Figure 6.15: Multiple terracotta pipes running beneath Byzantine street level with drains on either side of the road, in the Büyük Reşitpaşa Caddesi excavation (Source: Kerim Altuğ, personal communication)

As such they may be evidence of downstream networks associated with cisterns fed by the Aqueduct of Valens and the final part of the network that distributed water from the aqueducts, through the cisterns to the fountains where most people would have accessed their water supply.

However, as the photograph of this street is the only evidence of that downstream network, this part of the network is not considered in the study. The focus is placed on establishing likely connections between the main aqueduct routes and the cisterns. The network could connect the cisterns in two main ways: on-line (or in series) with water flowing from one cistern to the next, or off-line, with water leaving the main water flow in order to be stored in the cistern. The main disadvantages of an on-line storage system are that it requires a relatively steep drop in elevation from cistern to cistern in order to maintain the water channel close to the ground surface and it is difficult to isolate and empty a cistern (for cleaning or repair) without significant disruption to the downstream network. The off-line system results in more control mechanisms and therefore a higher management burden. In a small number of locations in Constantinople, the topography is sufficiently steep to allow the on-line arrangements and in some places, it is possible to trace a line of cisterns following the ridge line of a spur which might form a chain of connected cisterns, but in general an off-line system is more likely. The branches, diverting water from the main line to a cistern or a group of cisterns, would likely be marked by a control mechanism on the main line, however we have no evidence of any such control mechanisms, so have no concrete evidence on which to base the branch connections that will make up the complete water supply network. I have created branch connections based on the topography of the city, route of the aqueducts (almost all branches are taken from the Aqueduct of Valens in order to reflect the Justianic law code (11.42.6, trans Frier *et al.* 2016) which restricts use of the Aqueduct of Hadrian) and the position of cisterns that make up the 6th century network.

Two areas will now be considered in detail because the nature of the water network is more ambiguous: Hill One, where the source of water that filled the hill's many cisterns is uncertain and Hill Seven, where the role of the city's largest cistern is investigated.

### 6.6.1 Above ground or below? Water supply to Hill One

The water supply arrangements for Hill One were partially investigated in section 5.3.3, where it was concluded that rainwater harvesting could not have been the main source of water for the cisterns on this hill. Two possibilities remain – either water is supplied at a high level from the Aqueduct of Valens, or is lifted from the Aqueduct of Hadrian. The Topkapı Saray, the Ottoman Palace which is located on Hill One, was supplied in the 16th century from a high-level source (which makes use of *suterazi* water towers to cross the valley under pressure), a low-level source that lifted water from a large "well" in the grounds of the palace, and an *ayazma* or sacred spring (Necipoğlu 2013). The document discussed in Necipoğlu (2013) states that 10 lüles[71] of water are provided to the palace, though how this is divided between the two water lines and the *ayazma* are not clear. Andreossy's (1828, p. 422-4) summary of the Ottoman water supply makes it clear that the quantity of water in the high-level system (which used several aqueducts tapping the Halkalı springs) was not great, with the majority of the city's water supply in the lower Kırkçeşme system. This might explain the need for the two supply lines to the palace – the water provided by the high-level line would be convenient but the quantity would be insufficient for all the palace's needs, at which point the well could provide the extra water required. However, the structure was not truly a well. Rather than collecting ground water and reflecting the water table of the surrounding area, this structure was connected to a channel 18 m below the surface (Tezcan 1989, fig L6, Özkan Aygün 2010, p. 58) which was fed by the Kırkçeşme system. Tezcan (1989, p. 241-6) reports that at least one of the Ottoman wells was constructed around an older Byzantine-era well. Çeçen (1996a) associates these wells with the Hagia Sophia distribution centre which, he reports, also feeds the Basilica cistern.

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[71] 10 lüles equates to about 520 $m^3$/day (6 l/s), though it is worth noting an inconsistency in Necipoğlu's text, which states that a lüle is the water passed through a pipe of 73.59 mm diameter, which is significantly larger than the 26 mm diameter quoted by Çeçen. The figure of 73.59 mm appears to originate in an online government report (http://www.kultur.gov.tr/EN,117786/fountains-in-ottoman-istanbul.html accessed 25 January 2018) which states that: "the lüle pipe was defined as that through which a lead sphere weighing 30 dirhem (approximately 96.5 g) would pass, *i.e.* 73.58 mm." The density of lead is 11.3 g/$cm^3$ so the diameter of a 30 dirhem lead sphere would be 25.4 mm, not 73.58 mm (for a pipe of diameter 73.58 mm, the lead sphere would have a mass of 2.365 kg).

This lower level route under Hill One is perhaps more likely in the Byzantine era as well. As Hill Two is at about 50-54 masl and Hill One only 40-44 masl there is more than enough head to traverse the distance to Hill One, so the constraint on a high-level supply would be finding a workable route between the two hills. The high-level route would need to cross the valley between Hill One and Hill Two, either on a bridge or as a siphon. This part of the city was congested with large buildings and public spaces, with no obvious route for the water supply to take – the shortest route is blocked by the Hagia Sophia. A route to the north of the Hagia Sophia is made awkward by the Basilica on Hill Two (the porticoed space above rather than the cistern below) and, on Hill One, the church of Hagia Eirene and hospital. To the south, the route would need to negotiate the Augusteon, a public space surrounded by the Great Palace, Zeuxippos Baths and Hagia Sophia.

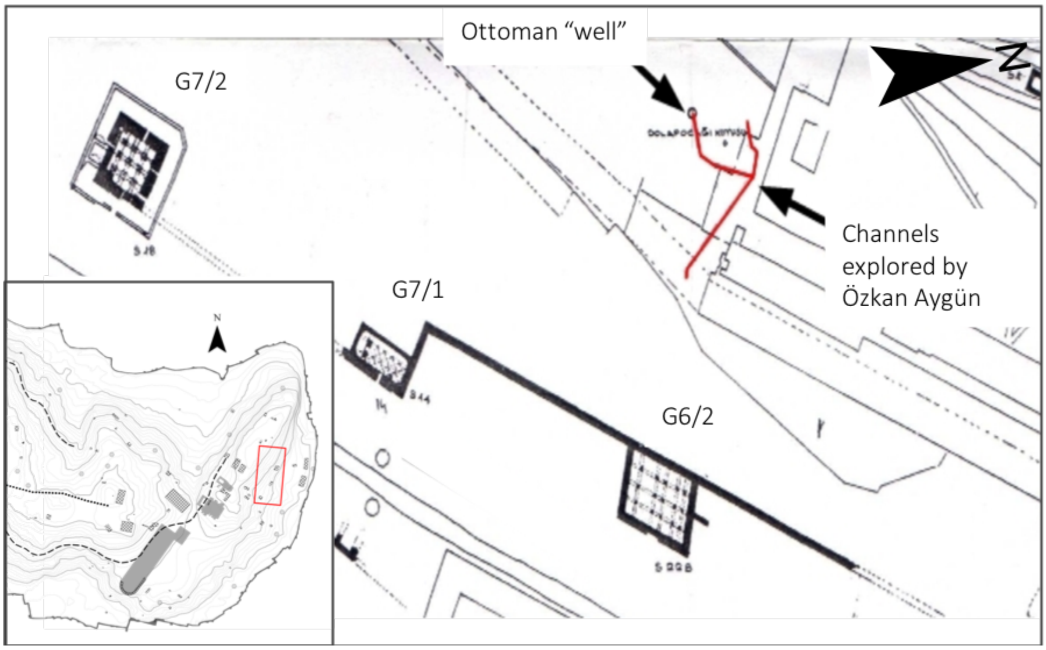
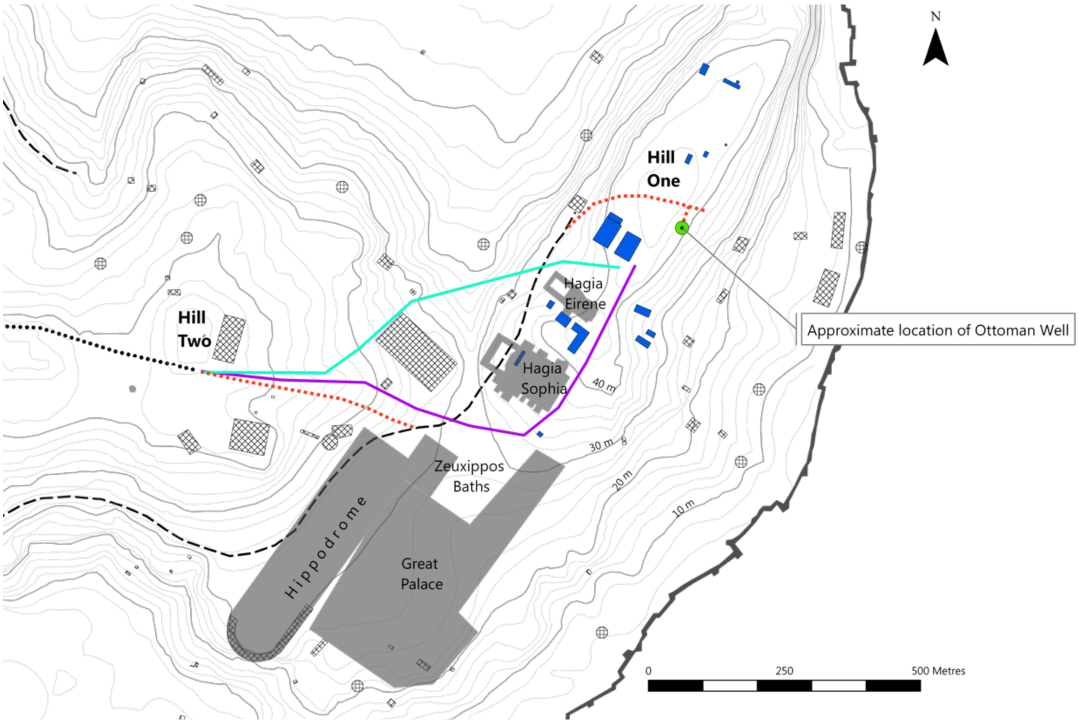


Figure 6.16: Routes of channels connected to the Ottoman well in the grounds of the Topkapı palace (pers. Comm. Özkan Aygün)

The evidence that the well and low-level Ottoman system replaced an earlier Byzantine-era one is not strong, based mainly on an anecdote that the position of the well was suggested in a dream and on investigation, an existing structure was revealed (Tezcan 1989, p. 241-6), however it is certainly possible. Özkan Aygün and her team of speleologists have managed a limited exploration of the channel connected to the large Ottoman well structure – the route that they mapped is shown in Figure 6.16. The channel is connected to two branches – one may have extended westwards towards the Basilica cistern and the source of water, and the other towards the other side of Hill One. If this arrangement dates to the Byzantine period, this eastern portion of the channel might be associated with the numerous cisterns on the far side of Hill One, three of which are pictured in Figure 6.16. These cisterns, some of which are of considerable size, are otherwise rather isolated from the rest of the network.



Map 6.11: Potential over ground routes of the Aqueduct of Valens to Hill One and underground route from the Aqueduct of Hadrian to Ottoman well. The cisterns highlighted are at an elevation that would require water to be lifted or to cross from Hill Two using a bridge or inverted siphon.

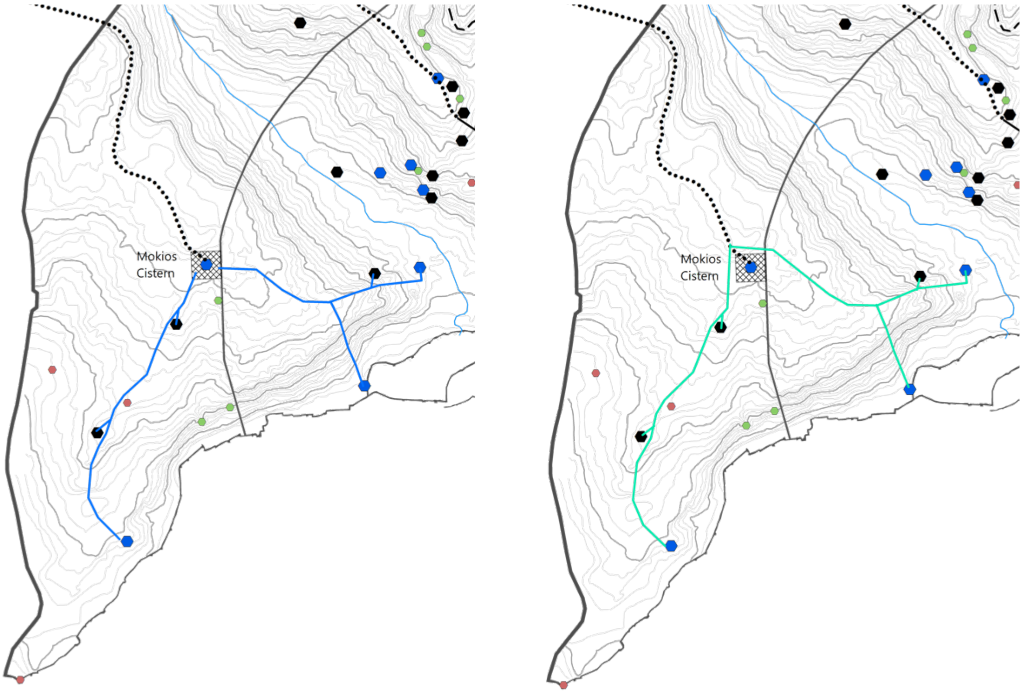
Although the low-level Kırkçeşme was the more abundant of the Ottoman systems, the opposite was the case in the Byzantine period, with the Aqueduct of Valens conveying much more water into the city than the Aqueduct of Hadrian. Even if the low-level route was used to get water to the top of Hill One, it is worth considering which source provided the water. The previous chapter established that the flow in Aqueduct of Hadrian was low relative to the Aqueduct of Valens and that its uses were restricted by law.

The large cisterns on Hill One would be a considerable additional burden that the Aqueduct of Hadrian might not have been able to support. Indeed, early model runs when the network was configured so that the Aqueduct of Hadrian was responsible for feeding Hill One proved unsuccessful with much of the aqueduct's water extracted by the baths and palace upstream of Hill One. However, it is conceivable that the Aqueduct of Valens, on reaching the end of the high ridge at Hill Two was dropped down to a lower level and either added to the Aqueduct of Hadrian or conveyed separately to feed the many cisterns on and around Hill One.

Map 6.11 illustrates both the possible high-level routes between Hill Two and Hill One and the potential low-level connection that tunnels beneath Hill One and is then lifted by a mechanical device to the peak of the hill and distributed amongst the cisterns there. The model is based on the Hill One cisterns being fed by the Aqueduct of Valens.

### 6.6.2 Water supply to Hill Seven – Mokios, the largest *Castellum Aquae?*

Mokios, an isolated open-air cistern on Hill Seven, is the largest known in Constantinople. Constructed in the early 6th century and measuring 170 x 147 m and 15 m in depth, it provides almost a third of the known storage volume within the city. Due to its size, it must have been fed by an aqueduct but the aqueduct source is uncertain. Perhaps Mokios was fed by a branch from the Valens Line, splitting off close to the Aetius Cistern and following a path back out of the Theodosian Wall, crossing the Lycus valley, and then re-entering the city on the north slope of Hill Seven (proposed in Crow, Bardill & Bayliss (2008, Map 12) See fig. 2.2 in Chapter 2), or the Lycus valley may have been crossed within the city's walls by an inverted siphon. Alternatively, Mokios may have been fed by a separate line taking water from the nearby Halkalı springs. It is difficult to conclude which option was preferred, but it seems unlikely that a water source so close to the city would go unused. Modern estimates of the yield of the Halkalı springs are relatively low (as discussed in Section 5.3.4), and the complexity of the Ottoman systems constructed to capture them perhaps show why the springs were not used as a primary source for the whole city, but that does not exclude them as a supply to the area around Hill Seven. Setting aside the source of water, the next question concerns the nature of the network on Hill Seven. Only 12 other cisterns have been discovered around Hill Seven, all at a lower elevation, three from each of the periods (including three unknown). It is possible that these cisterns were fed from Mokios rather than directly from an aqueduct, with the open-air cistern serving as an enormous *castellum aquae*. This idea is compatible with Mokios being supplied by a meagre source – the large size of the cistern ensuring that any excess inflow could be stored. The volume within the cistern would grow slowly over time but once established, the cistern would act as a safety buffer for the whole of Hill Seven. While this is a plausible use for Mokios, it is worth examining whether the largest storage capacity in the city provided other uses.



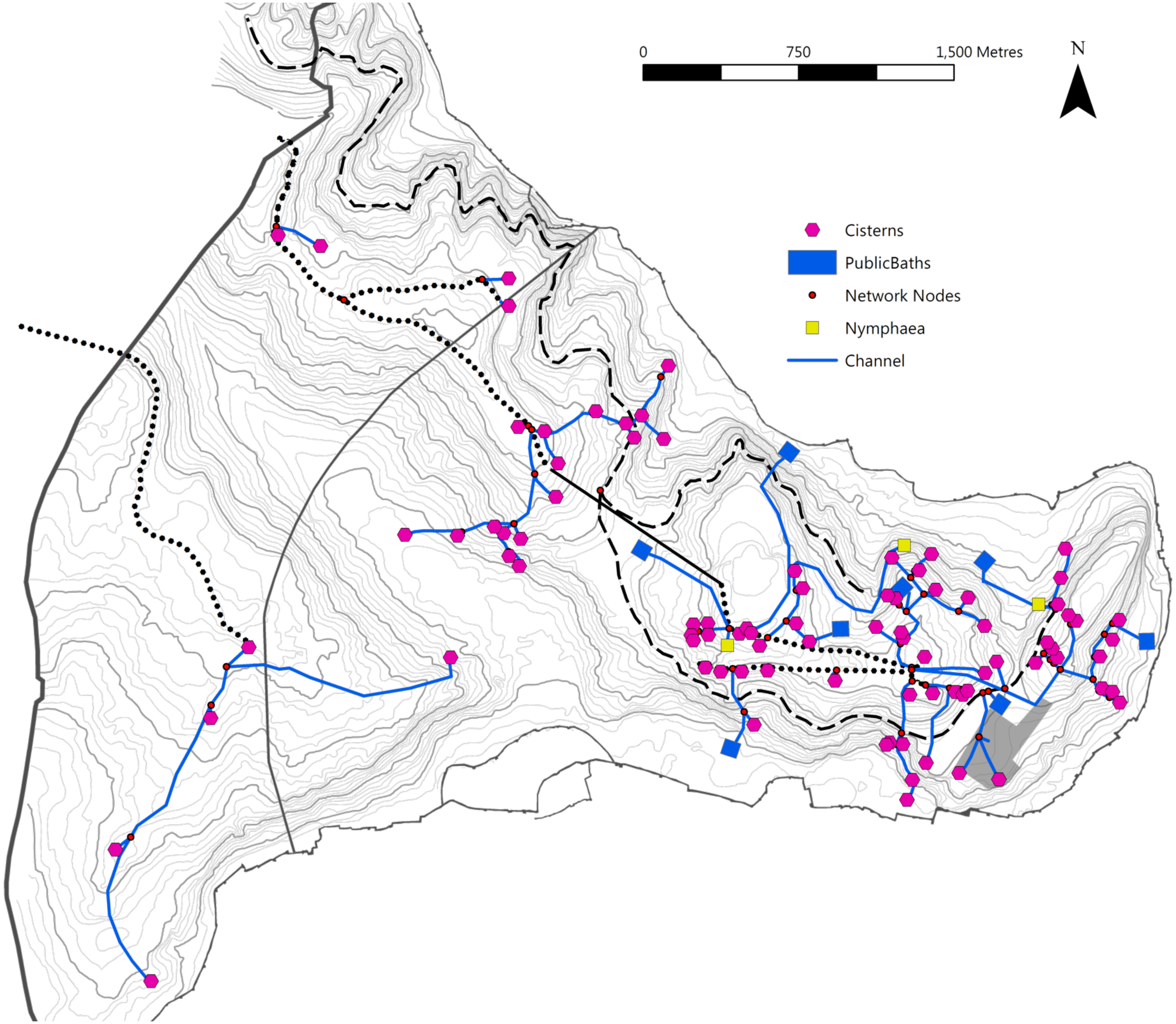
Map 6.12: Mokios connections – on the left Mokios acts as a *castellum aqua* and feeds the other cisterns (that are included in the model), and on the right Mokios is bypassed by channels from the aqueduct to feed the other cisterns directly.

Unlike the other large open-air cisterns of Aspar and Aetius, it is not likely that Mokios fed into another channel taking water into the city – Hill Seven is isolated by the Lycus and its valley from the rest of the city. Potentially, in this lower density area, there were agricultural or industrial requirements (for example, the *Notitia Urbis* places the Mint in Region XII – although this was long before the construction of Mokios). Although no evidence has been found either of structures controlling outflow from Mokios or channels distributing water across the hill, it is logical to conclude that as there is no strong evidence of a particular purpose for the water in Mokios, it was the source that fed the other cisterns on and around Hill Seven.

### 6.6.3 The network used in the model

Having examined all the individual elements of the physical infrastructure: the cisterns in Section 6.2, the Aqueduct of Hadrian in Section 6.3, the Aqueduct of Valens in Section 6.4 and the control mechanisms in Section 6.5 and considered potential options for the network around Hill One and Hill Seven, it is now possible to present how all the elements were likely to be connected. Cisterns are assumed to have been connected directly to the aqueduct when they are in close proximity to it and if not, to be connected to branch lines that connect to the aqueduct. Only the Mokios cistern is different: it is assumed to feed the other cisterns on Hill Seven.

The model represents the water supply system in the mid-6th century and combines the work on the physical infrastructure with the work on inflow and demand. The network that has been modelled comprises 87 cisterns, 78 nodes (representing control mechanisms) and 190 pipes and channels. The network is in a dendritic design, with branches off the main Aqueduct of Valens line feeding groups of cisterns. The arrangement of the network is shown in Map 6.13. With the exception of the Imperial Palace, Zeuxippos and Achilles Baths and the nymphaeum and cisterns in the vicinity of the Achilles Baths, everything is connected to the Aqueduct of Valens. In addition to all the cisterns, the Aqueduct of Valens provides water for six public baths and two nymphaea. At this stage, the proposed link from Aetius and Aspar to the Aqueduct of Hadrian has not been included in the main model.



Map 6.13: The modelled network.

## 6.7 Summary

The physical infrastructure is at the heart of the water supply and understanding it is critical to developing an understanding of the whole system. In this chapter, the work of Altuğ (2013) and Bardill (Crow, Bardill & Bayliss 2008) on cisterns and Crow, Bardill & Bayliss (2008) on the aqueduct routes within the city has been examined, extended and revised.

A total of 209 cisterns within the city has been established, an increase of a third on the comprehensive lists published by Altuğ (2013) and Bardill (Crow, Bardill & Bayliss 2008). The principle period of cistern construction was the early phase of Byzantine Constantinople, between the 4th and 7th centuries, although the largest group of cisterns are those of unknown or unassessed era. The spread of early period cisterns across the city ensured that people in most regions were no more than 250 m from a cistern, which conforms to modern minimum standards for water access. The cisterns are also spread across a range of elevations in the city from just above sea level to the highest points in the city. The majority of storage volume, is in the upper bands of elevation, associated with the large open-air cisterns. These cisterns are in contrast to the majority of cisterns which are much smaller and contribute a negligible amount to the total storage within the city. This indicates that cisterns act in different ways and have roles beyond merely providing storage. The majority of cisterns' main purpose is to support the distribution of water. Although the proximity to cisterns is relatively good across the city, factoring in both the storage within the cisterns and the variations in population density reveals a significant disparity in access to water. Overcoming that disparity would require careful management of the water resources entering the city.

The previously projected route for the Aqueduct of Hadrian, when assessed from an engineering perspective, was not valid; examining the interface between the topography and structures the aqueduct served and harnessing the later Ottoman system as a proxy, a new more likely route for the aqueduct has been established. The route, which crosses to the south side of the peninsula between Hills Three and Four is shorter than the northern option and provides better access to all the structures known to be supplied by the Aqueduct of Hadrian.

Assessing the precise route of the Aqueduct of Valens remains challenging although it is clear that in general terms it followed the ridge of high ground that makes up Hills Six to Two. New evidence of a sizeable channel on the ridge of Hill Five has altered the route of the channel upstream of the Bozdoğan Kemeri. Downstream of the bridge, the route around the Mese is uncertain and the purpose of the large, parallel, and connected channels identified at several points beneath the Mese has not been satisfactorily explained, although the pipes suggest that the Valens line may have doubled back to feed cisterns on the south side of the Mese. Beyond the Mese, it seems likely that the Aqueduct of Valens was responsible for feeding the cisterns around Hill One, though it is difficult to determine whether this was done by maintaining the channel's elevation on a structure crossing the valley between Hills One and Two or by dropping the water into the last section of the Aqueduct of Hadrian and then mechanically lifting water from a tunnel running under Hill One.

With no evidence found in Constantinople of how water was directed from the main aqueduct channels towards cisterns, examples from across the Roman Empire of regulation by vertically sliding gates are assumed to be representative of the technology used within the city. The examples of control mechanisms that do remain in Constantinople all relate to outflow from cisterns and demonstrate the level of sophistication that was possible.

Although there is little evidence of the network that connected aqueducts, cisterns and water users, its presence can be inferred from number and distribution of cisterns and the need to control and regulate this complex system. Most cisterns included in the model (that is, thought to be present in the 6th century) are fed by branches connecting groups or individual cisterns to the main Aqueduct of Valens channel. Hill Seven is judged to have a different arrangement from elsewhere, with the smaller cisterns fed from the Mokios cistern rather than directly from the aqueduct. It is also considered possible that the other open-air cisterns, Aetius and Aspar, were able to pass water down into the Aqueduct of Hadrian which enabled stored water to be moved from the periphery to the centre of the city. The Basilica cistern may have been constructed partly to facilitate this movement of large quantities of water.

The next chapter draws together the salient points of this chapter and the previous chapter on inflow and demand to present a model of the complete Constantinople water supply.

# An agent-based model of the operational system

## Why a model, why this type of model and why this scale - how does the model work - what can the model tell us

# VII

## 7.1 Introduction

This chapter brings everything together into a model of the water supply system, which provides a way of examining the assumptions and conclusions made for each of the elements, creates insight into how the system might have been managed and allows specific questions regarding the inflow, structural arrangements and the use of the largest cisterns to be addressed. An engineering perspective has already clarified and moved our understanding of the water supply forward: from cisterns to channels and from inflow figures to a distribution of demand. However, the aim has always been to consider the water supply as an operational system.

The model built in the Agent-Based Modelling software NetLogo contains both the physical distribution infrastructure – the pipes, control mechanisms and cisterns – and the consumers – the people and baths. An hourly inflow is distributed across the water supply network and is stored in the cisterns, from which the population can collect water to meet their daily water needs and baths draw the water necessary to keep them functioning. The performance of the system can be controlled by changing operation parameters of the network; performance data is recorded to allow comparison and development.

In this chapter I explore the development and use of the model in three broad parts: firstly, an examination of why a model is used and why the model was developed as it was; secondly, a description of the model and how it works; and, thirdly, the results of running the model with different scenarios and a consideration of what the model can tell us about the operation of the water supply system. This final section, considering what the model can tell us, is expanded upon in Chapter 8.

## 7.2 Aim of model

The model is a representation of the reimagined water supply of Constantinople, enabling the confirmation of assumptions and conclusions made thus far and the exploration of the actions necessary to ensure the satisfactory performance of the system.

### 7.2.1 Why agent-based modelling (ABM)?

An agent-based approach allows the modelling of complex social and engineered systems because individual components and behaviours can be specified and represented independently. It therefore offers the flexibility to develop the water supply network and collection parts of the model together and the sophistication to allow distributed control mechanisms of individual elements of the network. The ability to give the population a degree of agency creates a much more realistic pattern of water collection behaviour and offers opportunities for future development of the model.

This model is focused on consideration of the system as a whole and the performance on a human scale, therefore the model uses a mass-balance approach to the distribution of water through the network based on an hourly time unit. This excludes consideration of the hydraulic performance of the network, for which there is insufficient precise data and little to be gained for understanding the system as a whole.

### 7.2.2 Development of the model

The agent-based model presented here has its origins in an early attempt to consider how the cisterns could be used in the event of a siege. As this situation did not involve the movement of water between cisterns, just static water points, it was a relatively straightforward situation to consider and investigate with a model. I was interested not in how long the storage would last (which is a matter of arithmetic) but in the order that cisterns would empty and the distances that people would need to walk in order to get access to water as the cisterns emptied. The complexity of this task, the need to incorporate spatial decision making and measurement for thousands of people, quickly outgrew what a simple spreadsheet-based model could offer. Agent-based modelling offered a method of achieving these requirements and within the project team there was familiarity with the ABM software NetLogo.[72]

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[72] R Snyder was constructing a model in NetLogo to investigate the construction of the Aqueduct of Valens.

The insights and experience of building the prototype siege model convinced me that the agent-based modelling approach and NetLogo software would be suitable for attempting a full-scale connected network. The model presented in this chapter was developed from the original siege model and draws on a wide range of the sample models available with NetLogo and other online examples. Other, more industry-specific, software including drainage and water network modelling packages MicroDrainage and Infoworks had been considered and eliminated at an earlier stage, largely due to the relatively high data requirements and lack of flexibility for incorporating demand requirements.

### 7.2.3 Model scale

The initial proposal for the project focused on creating a hydraulic model of the network using proprietary software. However, it soon became clear that there was insufficient data to support such a model. The model developed in this study and presented here is based on a more straightforward mass-balance model, considering water as a volume to be distributed into smaller volumes throughout the network. This creates a different, higher-level focus much more attuned to the human scale of the system – the decision making necessary to manage such a complex distribution network and the access to water by the general public. It also facilitates the consideration of a relatively long time-period which could be difficult in a more computationally intensive hydraulic model. The longer period of consideration – a year – allows us to consider how the system had to cope and adapt to inflows changing with the seasons.

## 7.3 Mechanics of the model

The model combines the simulation of water passing through the network, which is a mass-balance discrete event simulation, and the simulation of water collection by the population, which uses an agent-based approach. That is to say, the inflow enters the upstream end of the distribution network and is shared across the network in accordance with the management rules. The population are then able to collect their daily water requirement from a cistern or nymphaeum. Water is also directed to each of the baths and “used” in two batches over the course of a day.

The population collects water in accordance with a set of rules (discussed further in Section 7.3.3) and each individual monitors whether they have been successful. The only aspect of their behaviour that can be changed is the volume of water they seek to collect. In contrast to this, the behaviour of the network can be closely controlled by altering the valve schedule and, in some cases, the addition of feedback loops that allow for more nuanced and variable control of inflow into the cisterns. The level of control over the two elements reflects reality – the network was an infrastructure system that would have been tightly managed whereas the population would act in their own interests (obtaining the water they need from as close to their home as possible) and could be only be loosely controlled, if at all, by the state.

### NetLogo Terminology

The NetLogo language has a number of key terms that are useful to define before proceeding further.

Agent-based models consist of agents, individual entities with properties that can represent elements within a system (Wilensky & Rand, 2015, p. 14, 22). These agents are unique, autonomous and able to interact with each other in the model environment (Railsback & Grimm, 2012, p. 10).

There are three types of agents in NetLogo, patches, turtles and links. Patches are non-mobile agents that make up the surface of the model. In this case the patches are only used to provide a visual display of Constantinople and indicate the population density of each region using a green colour scale. Links connect one agent to another and can allow information to pass along them. In the model links are used to represent pipes and channels. Turtles are mobile agents and in the model turtles are used to represent the population of Constantinople, the cisterns, the baths and the nodes (or control mechanisms). Ticks are the unit of time used within NetLogo. In the model of the water supply of Constantinople one tick equals one hour.

As the code for the model is too long to be usefully incorporated as an appendix, it has been stored on the University of Edinburgh Datashare. A diagram illustrating the major constituents of the model is shown in Figure 7.2, with further detail on each part in the following sections.

### Model verification

The model was verified using a parallel hand calculation that replicated the expected distribution of water for two ticks and compared this with the model results. Figure 7.3 is another form of verification, presenting a text version of the model code, illustrating how the distribution of water occurs within the network.

## 7.3.1 The inflow

The inflow enters the distribution at the most upstream nodes of the Aqueduct of Hadrian and the Aqueduct of Valens. To provide the granularity required to observe the filling and emptying of cisterns and the impact of management decisions, the unit of time within the model is hours. Therefore, the daily inflow (discussed in Section 5.3.1) has been split into 24 equal batches. The daily inflow data provided by F. Ruggeri (discussed in Section 5.3.1) for the Aqueduct of Valens is assumed to be delivered equally over the course of the day, so that the inflow into the system on each tick is 1/24 of the daily figure. For the Aqueduct of Hadrian (and, when relevant, the inflow from the Halkalı springs) flow is assumed to be constant throughout the year so the inflow into the model is a uniform amount based on the assumed daily yield (see Sections 5.3.2 and 5.3.4).

The model links ticks to time and so tracks the date and draws the relevant hourly rate from a table of values for each day of the year. The model runs slightly longer than a year,[73] beginning in October and running through to the following December. Therefore, the inflow values for October to December are used twice, at the beginning and end of the model run.

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[73] The model runs for 15 months (from 1 October 2001 to 31 December 2002 (arbitrary dates that avoid a leap year)). The first three months of the model run act as a warm up, giving time for the water stored within the cisterns to stabilise and to reflect that this is a continuously operating system, that would likely never start from empty. The first three months are excluded from analysis.

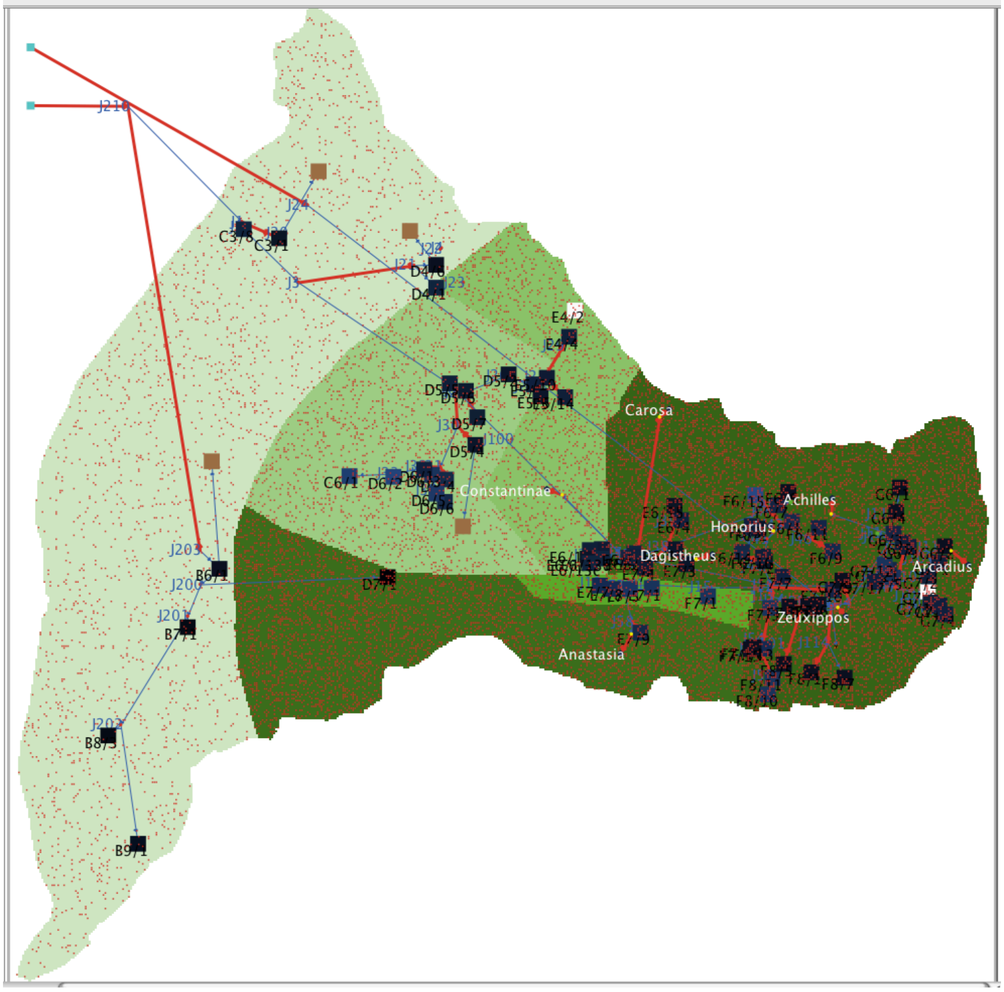

Figure 7.1: Screenshot showing how the network is represented in NetLogo

## 7.3.2 The network

The physical network is constructed from cisterns, nymphaea, baths, links and nodes. Cistern, bath and node locations are imported from GIS shape files and the links between them, representing the pipe connections, are defined in the set-up procedure. Figure 7.1 illustrates the network in the graphical interface of the model.

The cisterns are labelled with their code (as used in Appendix B) and are assigned their capacity and starting volume in the set-up procedure. Where the volume of the cistern is unknown, 1000 $m^3$ is assumed (this is a variable that can be altered uniformly across all the cisterns of unknown volume). The cisterns are represented by squares in the model that change colour to indicate how full they are from white when completely empty, through darkening shades of blue to black when the cistern is completely full. The links also change colour from blue to red to indicate when they are open (capacity equal to maximum capacity) or shut (capacity equal to zero).

There are eight different types of link, corresponding to a range of pipe capacities, detailed in Table 7.1. These pipe sizes (and capacities) do not have a direct link to evidence found within Constantinople rather the values used have developed over the course of making the model and have been driven by the need to balance and distribute water appropriately between branches and cisterns.

Each pipe is also given a number (1, 2 or 3) which is used in conjunction with the valve schedule to allow water to be managed, as discussed in Section 7.3.4 and Figure 7.3. Figure 7.4 (page 261) is a schematic of the system within the model showing the connection of channels, nodes, cisterns and baths.

Table 7.1: Capacity of pipes and channels used within the model

| Reference | Max capacity ($m^3$/hr) |
|---|---|
| D40 | 6 |
| D80 | 80 |
| D100 | 100 |
| D125 | 170 |
| D150 | 250 |
| D200 | 400 |
| D300 | 800 |
| Channel | 7000 |

### 7.3.3 The people

The people within the model represent one of the two demands put on the system (the other being the eight large public baths). As concluded in section 5.4, there is insufficient evidence to create a comprehensive, detailed understanding of water use across the city. Instead, the total water use (except the eight largest baths and the water supplied to the Great Palace) is assumed to be incorporated into the per capita demand.

### Population set-up

The population of Constantinople is represented in the model by 14,400 "persons" (the turtle breed defined within the model to represent the population), each representing 25 people (a one to one representation of population was too computationally demanding), so that the model considers the assumed peak population of 360,000 accessing water in the early 6th century (see Section 5.4.4). These "persons" are distributed during the model set-up to match the population density of each region (discussed in Section 5.4.4). Having a distributed population density more closely resembles reality than assuming a uniform distribution. People are most likely to have gone to nearby water supplies in order to minimise the distance that water needs to be carried.

Although the population of each region is the same each time the model runs, the exact position of each "person" is random, which leads to slight variation between models.[74] The original position of each "person" is recorded as their home point and is used when deciding which cistern to collect from. During the model set-up, each "person" is randomly assigned a water collection hour between 6am and 9pm. This collection time is the time that the "person" will start their water collection process each day. Having a distribution of collection times during the day roughly replicates water use throughout the day followed by a period of low water use during the night. It also prevents the huge drain on cisterns in a single tick that would occur if everyone tried to collect water as soon as each new day begins.

### Water collection

When the assigned collection hour occurs, each "person" selects a cistern or nymphaeum at random from the five nearest water providers (cisterns & nymphaea) to their home position. If that cistern has sufficient water to meet their requirements (that being 25 x *per capita* demand, in the phase 1 and 2 models this is 750 litres or 0.75 $m^3$), they remove the water from the cistern and

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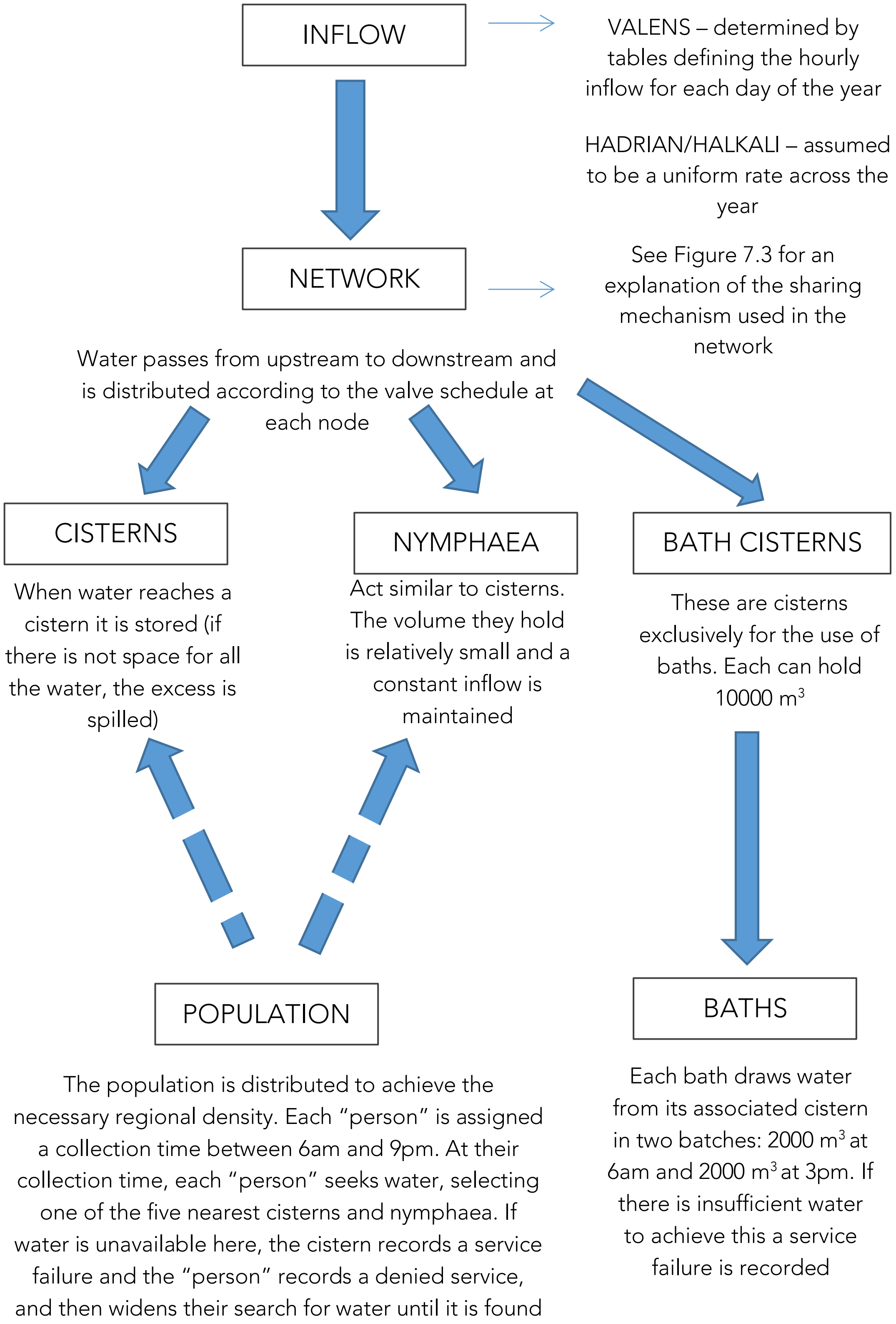
[74] This could potentially be considered a limitation in the model. However, I argue that it is a strength, introducing a low level of randomness between models that along with the ability of the population to select which cistern they visit each time, prevents the system being "fixed" such that it is manipulated to work for a given arrangement of population and inflow. If the system is able to manage across a number of model runs (all of which will be slightly different) it indicates a robustness in the management and the water supply system.

return home. If that cistern does not have enough water, a service failure is recorded by the cistern and the “person” records that they have been denied service and searches for water again, this time widening their search, selecting a cistern from the ten closest water providers to their current position (if another service failure occurs, the search widens to 15, and so on). The widening of the search prevents the unrealistic action of repeatedly selecting empty cisterns in the event that all five cisterns that are nearest to home being empty.

### 7.3.4 The management

Water passes through the network and at each node is divided according to the specific requirements at that node. A sharing mechanism, demonstrated in Figure 7.3, determines the way that water is divided at each node and the behaviour of the node can be varied hour to hour by the valve schedule. To distribute water, it is introduced to the furthest upstream node. Water is then “pulled” or requested by the downstream node or cistern from the node upstream. The amount delivered to the downstream node is determined by the pipe capacity between the upstream and downstream nodes or by the amount of water available at the upstream node. If the amount of water available at the upstream node is higher than the pipe capacity, then a volume of water equal to the pipe capacity is removed from the upstream node and made available at the downstream node. If the amount of water available is lower than the pipe capacity, a fraction of the available water is passed to the downstream node. That fraction is specified depending on the position in the network – for example in the initial versions of the model the fraction to take was uniformly set as a half, but this significantly skewed water distribution to the upstream branches, which were able to take half of a fairly sizeable amount compared to the downstream branches which were left taking halves of smaller and smaller amounts. In the current version, the fraction to be taken varies from $^{1}/_{20}$ to $^{4}/_{5}$ depending on location and performance requirements. Each node pulls/requests water in a specific order, with smaller branches pulling water before the larger ones to ensure that they get water. To enable controlled distribution a valve schedule enables the capacity of pipes to be turned to zero to simulate a control gate at the top of the pipe being closed. Currently this valve schedule is quite rigid, with the same daily pattern of closures repeating throughout the year, regardless of the inflow into the system. Some extra nuance has been added to overrule the valve schedule for branches leading to specific cisterns. A feedback loop enables the pipe capacity to be set to zero, or lowered, depending on the volume of water stored within the relevant cistern.



VALENS – determined by tables defining the hourly inflow for each day of the year

HADRIAN/HALKALI – assumed to be a uniform rate across the year

See Figure 7.3 for an explanation of the sharing mechanism used in the network

Water passes from upstream to downstream and is distributed according to the valve schedule at each node

When water reaches a cistern it is stored (if there is not space for all the water, the excess is spilled)

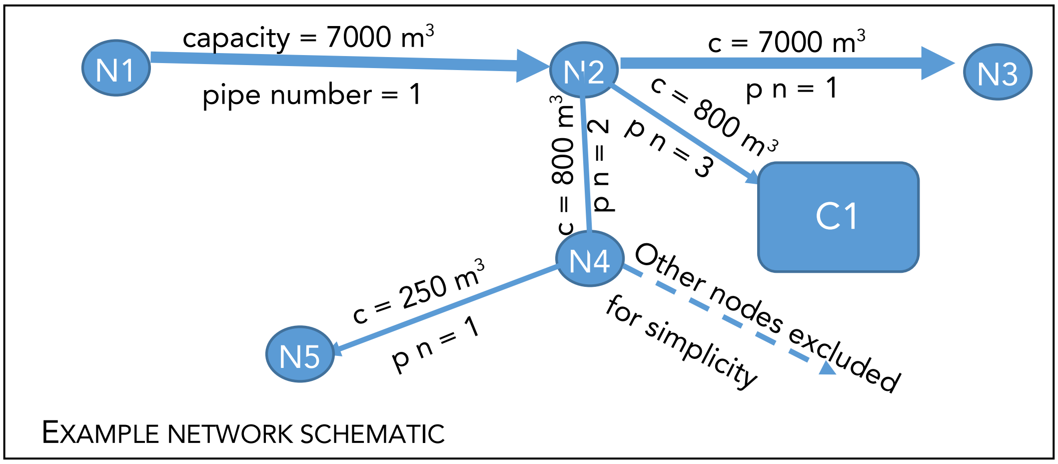
Act similar to cisterns. The volume they hold is relatively small and a constant inflow is maintained

These are cisterns exclusively for the use of baths. Each can hold 10000 m$^3$

The population is distributed to achieve the necessary regional density. Each “person” is assigned a collection time between 6am and 9pm. At their collection time, each “person” seeks water, selecting one of the five nearest cisterns and nymphaea. If water is unavailable here, the cistern records a service failure and the “person” records a denied service, and then widens their search for water until it is found

Each bath draws water from its associated cistern in two batches: 2000 m$^3$ at 6am and 2000 m$^3$ at 3pm. If there is insufficient water to achieve this a service failure is recorded

Figure 7.2: Diagram of model operation



WATER DISTRIBUTION SEQUENCE – REPLICATION OF THE MODEL CODE IN TEXT FORM

### Tick 1, valve schedule for N2 = 2 (pipe 1 open[75], pipe 2 open, pipe 3 closed)

1. Node 2 (N2) pulls water from N1, the amount available there is 4500 $m^3$ which is less than the pipe capacity. As it is the last node to pull from N1, it takes all the available water: 4500 $m^3$.
2. Cistern 1 pulls water from N2. Because it is served by a pipe with pipe number 3, it pulls 0 $m^3$
3. N4 pulls water from N2. The amount available is 4500 $m^3$ which is greater than the pipe capacity of 800 $m^3$. N4 takes water equal to its capacity and therefore has 800 $m^3$. N2 now has 3700 $m^3$ available.
4. N5 pulls water from N4. The amount available is 800 $m^3$ which is greater than the pipe capacity of 250 $m^3$. N5 takes water equal to its capacity and therefore has 250 $m^3$. N4 now has 550 $m^3$ available.
5. N3 pulls water from N2. The amount available is 3700 $m^3$ which is less than the pipe capacity. As it is the last node to pull from N2, it takes all the available water: 3700 $m^3$.

### Tick 2, valve schedule for N2 = 3 (pipe 1 open, pipe 2 closed, pipe 3 open)

1. Node 2 (N2) pulls water from N1, the amount available there is 700 $m^3$ which is less than the pipe capacity. As it is the last node to pull from N1, it takes all the available water: 700 $m^3$.
2. Cistern 1 pulls water from N2. The amount available is 700 $m^3$ which is less than the pipe capacity. It is not the last node to pull from N2, so it takes ¼ of the available flow,[76] 175$m^3$, and adds it to its total stored water.
3. N4 pulls water from N2. Because it is served by a pipe with pipe number 2, it pulls 0 $m^3$.
4. N5 pulls water from N4. The amount available is 0 $m^3$ so no water is transferred.
5. N3 pulls water from N2. The amount available is 525 $m^3$ which is less than the pipe capacity. As it is the last node to pull from N2, it takes all the available water: 525 $m^3$.

Figure 7.3: Explanation of the sharing mechanism used in the water distribution system

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[75] Pipes with pipe number 1 are always open.

[76] The share taken is dependent on location and performance requirements and is fixed in the code for each node/cistern.

### 7.3.5 Keeping track and performance indicators

In order to manage the water supply it is necessary to keep track of certain variables within the model. Some variables are reported to assess whether the performance has been satisfactory, others are used to understand how the system is behaving and to inform the changes to the management rules. Figure 7.5 (page 262) is a screenshot of the model's graphic interface that illustrates the large number of properties that are monitored within the model. The major properties that are tracked include the percentage of total capacity for each cistern, the number of people visiting each cistern, the number of service failures at each cistern, the spillage of excess water from cisterns and nodes, and for each of the baths, water available, spillage and number of failures are all recorded. The water available at the palace and failure of that supply are monitored, as is flow to each of the nymphaea and the number of people visiting them. Overall the total number of times people are denied service is recorded, as well as the total water spilled from cisterns and nodes.

The criteria for acceptable performance were introduced in Section 4.3.2 and relate to failures of service at cisterns, baths and the Imperial Palace. The year is split into two sections wet and dry, to accommodate the more precarious inflow in the drier months. Initially this split had been termed summer and winter but examination of the inflow data showed that October was typically the driest month, so the period in which poorer performance is accepted was extended to include it.

The performance indicators (see Table 7.2) have been slightly updated from Section 4.3.2, largely to put into concrete terms what constitutes a failure. For cisterns, the acceptable failure rate in the dry months was 15 days (10% of the 153 days in June to October) and in the wet months 6 days (3% of the 212 days in November to May, initially this was 2 days (1%) but I decided this was too onerous). For baths, it was 15 days (or 30 incidents as there are two chances to fail per day) in the dry months – the equivalent of three days per month – and in the wet months 1 day per month, or up to 7 days in total was deemed acceptable. In reality, the failures tended to occur in single events rather than spread throughout the months. In addition, the Imperial Palace had to maintain a constant 6 $m^3$/hr flow, however this proved straightforward to achieve as the water in the Aqueduct of Hadrian was restricted to relatively few users and the Great Palace was one of the furthest upstream users, which effectively guaranteed the flow would be available.

Table 7.2: Performance indicators used to assess model runs

| | Maximum number of service failures permissible | |
|---|---|---|
| | Wet months (Nov – May) | Dry months (Jun – Oct) |
| Cisterns | 6 | 15 |
| Baths | 7 | 15 |
| Great Palace | 0 | 0 |

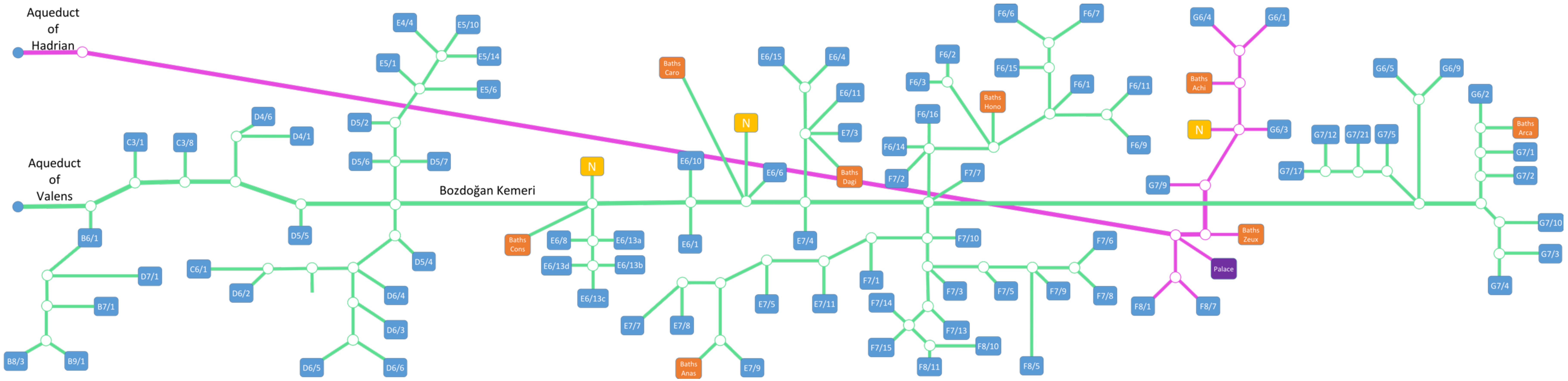
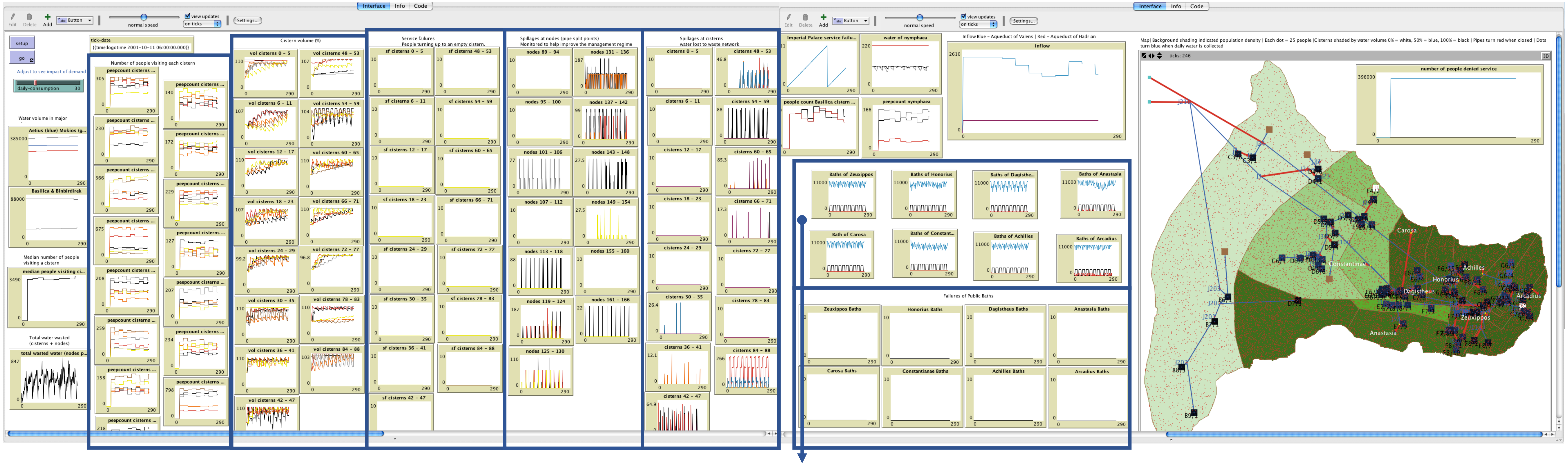


Figure 7.4: Schematic of the cisterns and connections included in the model



Measuring the number of people visiting each cistern every day

Measuring cistern volume 0-100%

Measuring the number of service failures at each cistern

Volume ($m^3$) of water spilled at each node

Volume ($m^3$) of water spilled at each cistern

Water volume ($m^3$) in bath feeder cistern

The number of service failures at each bath

Figure 7.5: Model screenshot showing the range of graphs that monitor the performance of the network.

## 7.4 Phase 1 Modelling

The bulk of the modelling was completed in two phases, with phase 1 using the concept model as its base. The concept model had been developed to enable water to pass through the system and into the cisterns and has been checked using a parallel hand calculation to ensure that the code behaved as intended. However little work had been done to optimise the management of the system.

The focus of the phase 1 modelling was to achieve an acceptable performance for one of the easier scenarios (at that stage I was uncertain whether it would be possible to achieve an acceptable performance in the more difficult scenarios). The different scenarios are defined by the inflow data used, represented by the graphs in Figures 5.5-5.8 in Chapter 5. These cover three different behaviours of the springs: non-reactive, where the inflow changes month to month but not day to day, a very smooth and predictable inflow; moderately-reactive where the inflow changes day to day in reaction to rainfall, creating peaks and troughs in the inflow representing periods of wet and dry weather; and highly-reactive which also changes in reaction to rainfall but in a more extreme way, creating higher peaks and lower troughs. For each spring there are data for four years of inflow, with Year 1 representing a lower than average flow, Years 2 and 3 representing average flow and Year 4 representing higher than average flow. Finally, there are the merged and parallel scenarios which capture the two possible arrangements of the aqueducts outside the city. In the parallel scenario, all the water that enters the aqueducts reaches the city, in the merged scenario the flow is restricted by the size of the channel and peak flows are spilled, resulting in a lower flow reaching the city. In total there are therefore 24 possible inflow scenarios for the model to use. The easiest are judged to be the parallel scenario for the non-reactive springs, Years 2, 3 and 4 because they provide the highest overall volume and a smooth flow with no serious low points. The most challenging are the opposite: the merged scenario for the highly reactive springs, Year 1 which has a low overall volume and highly changeable flow with very low troughs.

The phase 1 modelling aimed to set the network schedule and feedback rules so that the easiest inflow scenario (parallel, non-reactive springs, Year 2) had a satisfactory performance when the daily water demand was 30 litres *per capita*. This was done by identifying cisterns that were frequently empty in the concept model and investigating the pipe sizes that fed the cistern from the main channel and the number of hours a day that the cistern was able to receive flow. Altering these figures was generally sufficient to improve the performance somewhat. The investigation also looked at where water was being lost unnecessarily for example where high volumes were consistently spilled from cisterns or nodes, in these cases reducing the number of hours pipes were open reduced or eliminated the spill and therefore made the water available elsewhere in the system. Overall, the approach in phase 1 was to make sure that each cistern got enough water to meet the demand.

When this had been achieved, the same set of rules was applied to each of the 24 inflow scenarios (assuming that Mokios was fed by the Aqueduct of Valens).

### Results

The results of the phase 1 modelling are shown in Table 7.3 and Table 7.4, which detail the performance of the cisterns and baths respectively. The performance of the Great Palace was satisfactory throughout all the model runs, so this has not been recorded in a table. In total, seven of the 24 inflow scenarios had an acceptable performance using the phase 1 management arrangements. Of the 12 parallel models, five pass the cistern performance criteria and four of those also pass the bath performance criteria. Additionally, MRY3 (moderately reactive, Year 3) is very close to passing both the bath and cistern criteria. Of the 12 merged models, three pass both the cistern and bath performance criteria.

Table 7.3: Phase 1 modelling – cistern service failure results. Cisterns that do not appear in the table have no service failures in any inflow scenario. The inflow scenarios that pass (i.e. all cisterns perform within acceptable limits) are shaded yellow. Inflow scenarios where at least one cistern has service failures outwith acceptable limits are considered to fail and are shaded blue.

No service failures

Service failures are within acceptable limits (<7/<16)

Service failures are outwith acceptable limits and therefore constitute a fail for the cistern and the inflow scenario

**PARALLEL** total service failure days (wet months/dry months)

| | Cisterns | E6/4 | E6/15 | F6/14 | F7/2 | F6/16 | F6/2 | F6/3 | F6/1 | F6/15 | F6/7 | F6/6 | F6/11 | F7/9 | F7/8 | F7/14 | F7/15 | F8/11 | G7/21 | G7/17 | G7/3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INFLOW SCENARIOS | NRY1 | | | | 22 (0/22) | 13 (0/13) | 29 (0/29) | 25 (0/25) | 28 (0/28) | 32 (0/32) | 40 (0/40) | 54 (0/54) | 27 (0/27) | | | 56 (1/55) | 4 (0/4) | | | | 121 (62/59) |
| | NRY2 | | | | | | | | | | | | | | | | | | | | |
| | NRY3 | | | | | | | | | | | | | | | | | | | | |
| | NRY4 | | | | | | | | | | | | | | | | | | | | |
| | MRY1 | | | | 14 (0/14) | 8 (0/8) | 47 (8/39) | 39 (5/34) | 35 (5/30) | 82 (20/62) | 41 (5/36) | 73 (16/57) | 38 (5/33) | | | 69 (3/66) | 5 (0/5) | 34 (0/34) | | | 120 (44/76) |
| | MRY2 | | | | | | | | | 15 (6/9) | | 9 (2/7) | | | | 6 (6/0) | | | | | |
| | MRY3 | | | | | | | | | | | | | | | 9 (9/0) | | | | | |
| | MRY4 | | | | | | 3 (0/3) | | 1 (0/1) | 11 (0/11) | | 12 (0/12) | | | | 5 (5/0) | | | | | |
| | HRY1 | 11 (3/8) | 33 (11/22) | 12 (3/9) | 32 (11/21) | 19 (6/13) | 89 (43/46) | 81 (39/42) | 72 (34/38) | 139 (72/67) | 65 (29/36) | 114 (55/59) | 50 (22/28) | 7 (7/0) | 5 (0/5) | 118 (54/64) | 5 (0/5) | 30 (10/20) | | 3 (0/3) | 170 (79/91) |
| | HRY2 | 2 (0/2) | 8 (1/7) | | 5 (0/5) | 1 (0/1) | 16 (4/12) | 11 (2/9) | 9 (2/7) | 50 (30/20) | 13 (0/13) | 34 (15/19) | 9 (0/9) | | | 14 (5/9) | | | | | 2 (2/0) |
| | HRY3 | | | | 9 (8/1) | 3 (3/0) | 42 (19/23) | 31 (18/13) | 35 (16/19) | 66 (31/35) | 34 (20/14) | 54 (26/28 | 25 (17/8) | | | 30 (14/16) | | 13 (13/0) | | | |
| | HRY4 | 6 (0/6) | 15 (0/15) | 6 (0/6) | 10 (0/10) | 8 (0/8) | 33 (4/29) | 27 (5/22) | 21 (2/19) | 66 (17/49) | 21 (2/19) | 49 (10/39) | 12 (0/12) | | | 26 (0/26) | | 2 (0/2) | | | |

**MERGED** total service failure days (wet months/dry months)

| | Cisterns | E6/4 | E6/15 | F6/14 | F7/2 | F6/16 | F6/2 | F6/3 | F6/1 | F6/15 | F6/7 | F6/6 | F6/11 | F7/9 | F7/8 | F7/14 | F7/15 | F8/11 | G7/21 | G7/17 | G7/3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INFLOW SCENARIOS | NRY1 | | | | 22 (0/22) | 11 (0/11) | 29 (0/29) | 26 (0/26) | 28 (0/28) | 32 (0/32) | 36 (0/36) | 53 (0/53) | 29 (0/29) | | | 57 (1/56) | | | | | 131 (54/77) |
| | NRY2 | | | | | | | | | | | | | | | | | | | | |
| | NRY3 | | | | | | | | | | | | | | | | | | | | |
| | NRY4 | | | | | | | | | | | | | | | | | | | | |
| | MRY1 | | | | 15 (1/14) | 9 (0/9) | 47 (7/40) | 40 (4/36) | 40 (5/35) | 83 (21/62) | 44 (5/39) | 72 (16/56) | 34 (4/30) | | | 85 (13/72) | 5 (0/5) | 40 (0/40) | | | 316 (184/132) |
| | MRY2 | | | | | | | | | 17 (7/10) | | 9 (2/7) | | | 64 (0/64) | 7 (7/0) | | | | | 349 (201/148) |
| | MRY3 | | | | | | | | | | | | | | 182 (75/107) | 6 (6/0) | | | | | 330 (192/138) |
| | MRY4 | | | | | | 3 (0/3) | | 2 (0/2) | 12 (0/12) | | 17 (0/17) | | | 16 (0/16) | 3 (3/0) | | | | | 332 (207/125) |
| | HRY1 | 13 (4/9) | 35 (11/24) | 9 (2/7) | 30 (11/19) | 18 (5/13) | 86 (42/44) | 76 (37/39) | 69 (33/36) | 133 (70/63) | 72 (31/41) | 122 (59/63) | 52 (23/29) | 7 (7/0) | | 125 (60/65) | 8 (0/8) | 56 (23/33) | 10 (8/2) | | 302 (173/129) |
| | HRY2 | 2 (0/2) | 7 (1/6) | | 3 (0/3) | | 13 (3/10) | 16 (6/10) | 9 (2/7) | 46 (27/19) | 15 (2/13) | 37 (18/19) | 9 (0/9) | | 104 (33/71) | 18 (8/10) | | | | | 342 (193/149) |
| | HRY3 | | | | 10 (9/1) | 4 (4/0) | 42 (19/23) | 33 (17/16) | 34 (15/19) | 65 (32/33) | 39 (21/18) | 54 (26/28) | 29 (18/11) | | 14 (6/8) | 33 (14/19) | 5 (5/0) | 15 (15/0) | | | 343 (201/142) |
| | HRY4 | 9 (0/9) | 17 (0/17) | 6 (0/6) | 11 (0/11) | 8 (0/8) | 32 (5/27) | 29 (5/24) | 24 (3/21) | 70 (21/49) | 23 (2/21) | 52 (12/40) | 15 (0/15) | | 84 (32/52) | 27 (0/27) | | 6 (0/6) | | 2 (0/2) | 358 (208/150) |

Table 7.4: Phase 1 modelling – bath service failures. The inflow scenarios that pass (i.e. all baths perform within acceptable limits) are shaded yellow. Inflow scenarios where at least one bath has service failures outwith acceptable limits are considered to fail and are shaded blue.

| 🟩 | 🟨 | 🟦 |
|---|---|---|
| No service failures | Service failures are within acceptable limits <8\|<16 | Service failures are outwith acceptable limits and therefore constitute a fail for the bath and the inflow scenario |

**P A R A L L E L** total service failure days

| | | Achilles | | Anastasia | | Arcadius | | Carosa | | Constantianae | | Dagistheus | | Honorius | | Zeuxippos | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | W | D | Wet | Dry | Wet | Dry | W | D | W | D | Wet | Dry | Wet | Dry | W | D |
| INFLOW SCENARIOS | 🟦 NRY1 | 🟩 | 🟩 | 🟦 17.5 | 🟦 31 | 🟩 | 🟦 70 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟦 39.5 | 🟩 | 🟩 |
| | 🟨 NRY2 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | 🟨 NRY3 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | 🟨 NRY4 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | 🟦 MRY1 | 🟩 | 🟩 | 🟦 22 | 🟦 15.5 | 🟦 30 | 🟦 68 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 4 | 🟦 17.5 | 🟦 55.5 | 🟩 | 🟩 |
| | 🟨 MRY2 | 🟩 | 🟩 | 🟨 0.5 | 🟨 2.5 | 🟨 3.5 | 🟨 12 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 4 | 🟨 8.5 | 🟩 | 🟩 |
| | 🟦 MRY3 | 🟩 | 🟩 | 🟨 1.5 | 🟨 8 | 🟦 7.5 | 🟨 10.5 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 1 | 🟩 | 🟩 |
| | 🟦 MRY4 | 🟩 | 🟩 | 🟨 0 | 🟨 9.5 | 🟨 1.5 | 🟦 17.5 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 10 | 🟩 | 🟩 |
| | 🟦 HRY1 | 🟩 | 🟩 | 🟦 42 | 🟦 48 | 🟦 70 | 🟦 77 | 🟩 | 🟩 | 🟩 | 🟩 | 🟦 20 | 🟦 33.5 | 🟦 59 | 🟦 62 | 🟩 | 🟩 |
| | 🟦 HRY2 | 🟩 | 🟩 | 🟨 6 | 🟨 13 | 🟦 15.5 | 🟨 15 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 5 | 🟨 12 | 🟦 17 | 🟦 17.5 | 🟩 | 🟩 |
| | 🟦 HRY3 | 🟩 | 🟩 | 🟦 11 | 🟨 15 | 🟦 22 | 🟦 24.5 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 1.5 | 🟨 2.5 | 🟦 23 | 🟦 29 | 🟩 | 🟩 |
| | 🟦 HRY4 | 🟩 | 🟩 | 🟨 3.5 | 🟦 24.5 | 🟦 10.5 | 🟦 33.5 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟦 20.5 | 🟦 11 | 🟦 38 | 🟩 | 🟩 |

**M E R G E D** total service failure days

| | | Achilles | | Anastasia | | Arcadius | | Carosa | | Constantianae | | Dagistheus | | Honorius | | Zeuxippos | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INFLOW SCENARIOS | 🟦 NRY1 | 🟩 | 🟩 | 🟦 19 | 🟦 32.5 | 🟨 0.5 | 🟦 70.5 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟦 40 | 🟩 | 🟩 |
| | 🟨 NRY2 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | 🟨 NRY3 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | 🟨 NRY4 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | 🟦 MRY1 | 🟩 | 🟩 | 🟦 78 | 🟦 42 | 🟦 33 | 🟦 70 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 4.5 | 🟦 15.5 | 🟦 56 | 🟩 | 🟩 |
| | 🟦 MRY2 | 🟩 | 🟩 | 🟦 79.5 | 🟦 59.5 | 🟨 3.5 | 🟨 12.5 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 4.5 | 🟨 7.5 | 🟩 | 🟩 |
| | 🟦 MRY3 | 🟩 | 🟩 | 🟦 78.5 | 🟦 63 | 🟨 6.5 | 🟨 11.5 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 1 | 🟨 1.5 | 🟩 | 🟩 |
| | 🟦 MRY4 | 🟩 | 🟩 | 🟦 73 | 🟦 56.5 | 🟨 1 | 🟦 19 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 11.5 | 🟩 | 🟩 |
| | 🟦 HRY1 | 🟩 | 🟩 | 🟦 83.5 | 🟦 61 | 🟦 76.5 | 🟦 82.5 | 🟩 | 🟩 | 🟩 | 🟩 | 🟦 19 | 🟦 34.5 | 🟦 60.5 | 🟦 61.5 | 🟩 | 🟩 |
| | 🟦 HRY2 | 🟩 | 🟩 | 🟦 76.5 | 🟦 68 | 🟦 23 | 🟦 16 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 4 | 🟨 12 | 🟦 18 | 🟦 18 | 🟩 | 🟩 |
| | 🟦 HRY3 | 🟩 | 🟩 | 🟦 85 | 🟦 60 | 🟦 24 | 🟦 27 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 1.5 | 🟨 2.5 | 🟦 23.5 | 🟦 29 | 🟩 | 🟩 |
| | 🟦 HRY4 | 🟩 | 🟩 | 🟦 69.5 | 🟦 66 | 🟦 13.5 | 🟦 36.5 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟦 20.5 | 🟦 13.5 | 🟦 39 | 🟩 | 🟩 |

## 7.5 Phase 2 Modelling

Phase 2 modelling focuses on achieving an acceptable performance for a much more challenging inflow scenario, the Year 2 flow with merged aqueducts and highly reactive springs. This is not the worst scenario, which is the Year 1 flow, but it is the worst average flow scenario. To reach an acceptable performance, the focus moved from just ensuring that each cistern got enough by means of manipulating the hours that cisterns received water towards preventing cisterns from receiving too much water. For the merged scenario, the total volume of water available was considerably lower so preventing unnecessary spillage was of far greater importance. Any water spilled in the upstream area was lost to the downstream areas. It was noticeable that the performance of the Anastasia and Arcadius Baths was very poor. Both baths are located at the end of branches and so were effectively the last to receive water, any upstream mistakes in management had a severe impact on these water users. As a result, simply altering the valve schedule was insufficient to improve performance. Feedback loops were used extensively to keep the cisterns at less than full, typically switching off inflows when the cistern reached 80-90% capacity. This is quite a defensive strategy and could be a disadvantage during an extended dry period as cisterns have less storage to draw on, it is only really suitable for occasions when the inflow was low but reliable.

### Results

Table 7.5 shows the performance of cisterns and Table 7.6 the performance of baths in the phase 2 modelling. There is a clear improvement in performance between phase 1 and phase 2. In phase 2, only one cistern, F7/14, has service failures, and only in six of the 24 inflow scenarios. In only two scenarios, HRY1 (highly-reactive Year 1), for both merged and parallel, are the service failures outwith the permitted failure levels. There is a similar improvement in the performance of the baths, and again the only occasions that an unacceptable level of failures occur are in the merged and parallel scenarios for HRY1.

Table 7.5: Phase 2 modelling – cistern service failure results. Cisterns that do not appear in the table have no service failures in any inflow scenario. The inflow scenarios that pass (i.e. all cisterns perform within acceptable limits) are shaded yellow. Inflow scenarios where at least one cistern has service failures outwith acceptable limits are considered to fail and are shaded blue.

| | | |
|---|---|---|
| 🟩 No service failures | 🟨 Service failures are within acceptable limits (<7/<16) | 🟦 Service failures are outwith acceptable limits and therefore constitute a fail for the cistern and the inflow scenario |

| | | **PARALLEL** | **MERGED** |
|---|---|---|---|
| | | total service failure days (wet months/dry months) | |
| | Cistern | F7/14 | F7/14 |
| INFLOW SCENARIOS | 🟨 NRY1 | 🟩 | 🟩 |
| | 🟨 NRY2 | 🟩 | 🟩 |
| | 🟨 NRY3 | 🟩 | 🟩 |
| | 🟨 NRY4 | 🟩 | 🟩 |
| | 🟨 MRY1 | 🟩 | 🟩 |
| | 🟨 MRY2 | 🟩 | 🟩 |
| | 🟨 MRY3 | 🟩 | 🟩 |
| | 🟨 MRY4 | 🟩 | 🟩 |
| | 🟦 HRY1 | 🟦 25 (9/16) | 🟦 30 (10/20) |
| | 🟨 HRY2 | 🟨 7 (4/3) | 🟨 11 (6/5) |
| | 🟨 HRY3 | 🟩 | 🟩 |
| | 🟨 HRY4 | 🟨 15 (0/15) | 🟨 11 (0/11) |

Table 7.6: Phase 2 modelling – bath service failures. The inflow scenarios that pass (i.e. all baths perform within acceptable limits) are shaded yellow. Inflow scenarios where at least one bath has service failures outwith acceptable limits are considered to fail and are shaded blue.

| No service failures | Service failures are within acceptable limits <8\|<16 | Service failures are outwith acceptable limits and therefore constitute a fail for the bath and the inflow scenario |
|---|---|---|

**PARALLEL** total service failure days

| | | Achilles | | Anastasia | | Arcadius | | Carosa | | Constantianae | | Dagistheus | | Honorius | | Zeuxippos | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | W | D | Wet | Dry | Wet | Dry | W | D | W | D | Wet | Dry | Wet | Dry | W | D |
| INFLOW SCENARIOS | NRY1 | | | | 9.5 | | | | | | | | | | | | |
| | NRY2 | | | | | | | | | | | | | | | | |
| | NRY3 | | | | | | | | | | | | | | | | |
| | NRY4 | | | | | | | | | | | | | | | | |
| | MRY1 | | | 1 | 6 | | 9 | | | | | | | | | | |
| | MRY2 | | | | | | | | | | | | | | | | |
| | MRY3 | | | | | | | | | | | | | | | | |
| | MRY4 | | | | 1 | | | | | | | | | | | | |
| | HRY1 | | | 8.5 | 17 | 18.5 | 25 | | | | | | | 2.5 | 8.5 | | |
| | HRY2 | | | 1 | 5 | | 5.5 | | | | | | | 2.5 | 8.5 | | |
| | HRY3 | | | 2.5 | 1 | 3 | 7.5 | | | | | | | | | | |
| | HRY4 | | | | 8.5 | | 12.5 | | | | | | | | 6 | | |

**MERGED** total service failure days

| | | Achilles | | Anastasia | | Arcadius | | Carosa | | Constantianae | | Dagistheus | | Honorius | | Zeuxippos | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INFLOW SCENARIOS | NRY1 | | | | 9 | | | | | | | | | | | | |
| | NRY2 | | | | | | | | | | | | | | | | |
| | NRY3 | | | | | | | | | | | | | | | | |
| | NRY4 | | | | | | | | | | | | | | | | |
| | MRY1 | | | 0.5 | 6 | | 9 | | | | | | | | | | |
| | MRY2 | | | | | | | | | | | | | | | | |
| | MRY3 | | | | | | | | | | | | | | | | |
| | MRY4 | | | | 0.5 | | | | | | | | | | | | |
| | HRY1 | | | 8 | 18 | 19 | 24.5 | | | | | | | 2.5 | 7.5 | | |
| | HRY2 | | | 0.5 | 5.5 | | 4.5 | | | | | | | 0.5 | 2 | | |
| | HRY3 | | | 4 | 1.5 | 2.5 | 7.5 | | | | | | | | | | |
| | HRY4 | | | | 8.5 | | 13.5 | | | | | | | | 5 | | |

## 7.6 Further modelling

Having completed the phase 1 and 2 modelling stages, three further questions have been considered and some additional modelling carried out to attempt to answer them. Firstly, the sensitivity of the model to *per capita* demand is investigated. The initial modelling has been completed with the *per capita* demand at the lower end of the spectrum, representing a situation with low overall water use. Secondly the possibility that the Mokios cistern and Hill Seven cisterns were fed by the Halkalı spring, raised as a possibility in Section 5.3.4, is investigated. If this area could have been sustained by this low yield spring, it would result in more of the flow in the Aqueduct of Valens being available to the other parts of the system. Thirdly, the impact of filling the largest cisterns is investigated. If these cisterns served in any capacity other than emergency reservoirs, they would regularly be emptied and filled to some degree and the impact of diverting large quantities of water into these structures on the rest of the downstream network needs to be understood.

### 7.6.1 Sensitivity to *per capita* demand

Initially the *per capita* demand was raised to 50 litres/day for the PH2ParMRY2 and PH2MerMRY2 (phase 2 parallel and merged models for the Moderately reactive spring Year 2). The result was rapid failure of cisterns in a number of areas. At no point did the volume in these cisterns recover and the denied service figures were consistently high throughout the model. Interestingly, the performance of the baths in these models did not see a similar deterioration – with the exception of the Achilles Baths, which are located at the end of the Aqueduct of Hadrian – this indicates how finely balanced the flow in the Aqueduct of Hadrian is with the demands placed on it – even with the small number of cisterns associated with the line, the slight increase in volume taken from the cisterns led to a steady decline in the water available for the Achilles Baths and a small but regular failure of the bath. In the merged and parallel versions of the model the same 31 cisterns failed and did so to the same extent. This is despite there being more water available (at times) in the parallel version. The lack of difference between the two results indicates that the failures are not simply due to insufficient water for the higher demand – this is in part a failure of the management scenario, which had been optimised around the 30 l/head/day value.

When the phase 1 ParMRY2 model was run with the higher demand figure, the results were interesting. Although there was widespread failure of cisterns (a total of 36 cisterns failed – higher than in the phase 2 models), the denied service level is much lower. Cisterns do empty and cause failures but less frequently and less consistently than in the phase 2 models. I believe this is because the less restrictive management rules enable the system to take better advantage of the periods when inflow is higher.

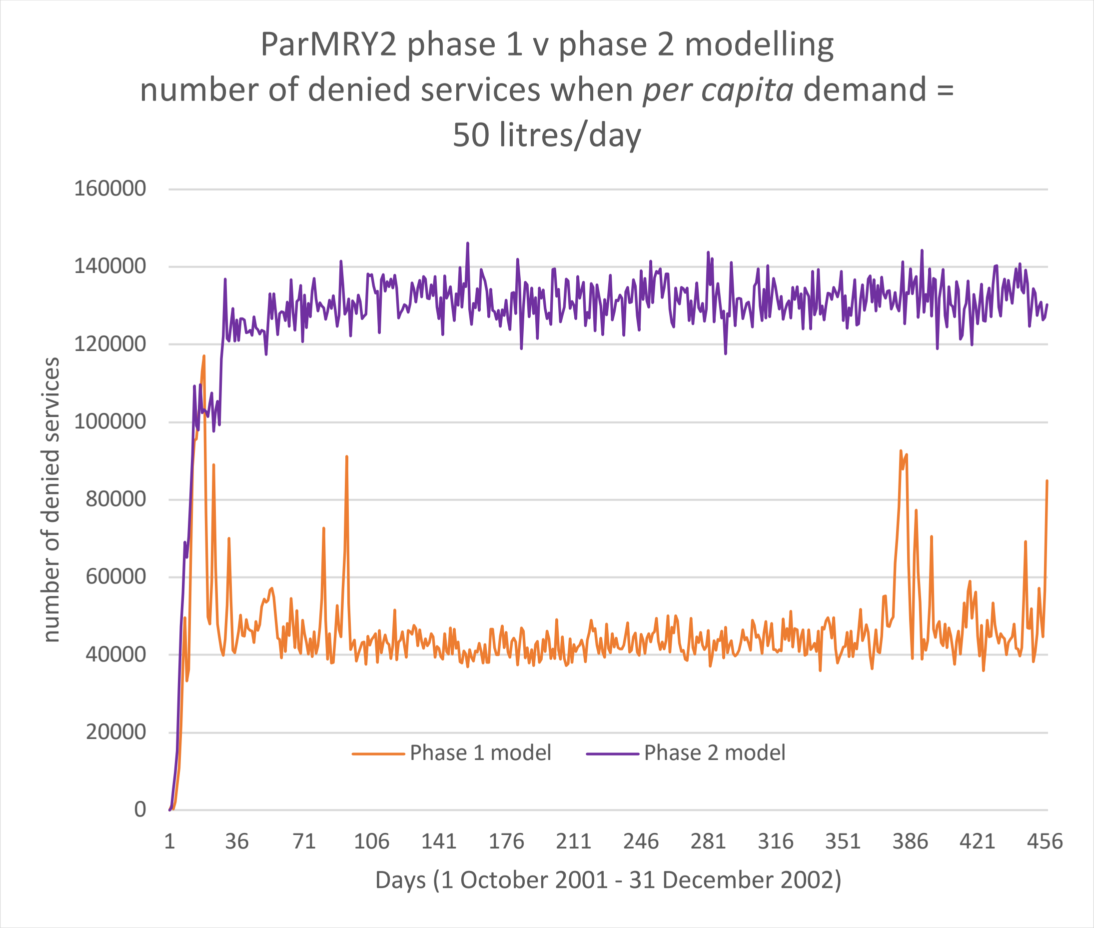


Figure 7.6: Sensitivity to *per capita* demand:comparison of total number of "denied services" for the ParMRY2 model with a per capita demand of 50 litres/day for the phase 1 and phase 2 models.

Neither result directly answers the question of whether the system could cope with a higher *per capita* demand – further alterations to the management rules and valve schedule are needed. However, the significant improvement in performance between the two phases suggests that with purposeful alterations to the management rules, even further improvements are possible.

### 7.6.2 Mokios fed by the Halkalı spring

The model was restructured to allow the flat rate assumed for the Halkalı spring inflow to be delivered to the node immediately upstream of Mokios. The results clearly show that if the spring provided the yield (equivalent to 4212 $m^3$/day), it is sufficient to fill (albeit slowly) the Mokios cistern, supply the four other cisterns on Hill Seven and meet the local population's water demand of 30 litres *per capita*. Further investigations need to consider the impact of a variable inflow from Halkalı, whether Mokios would be able to satisfactorily support high volume users and also the positive impact on the rest of the system created by removing Hill Seven from the responsibility of the Aqueduct of Valens.

### 7.6.3 The impact of filling the large cisterns

The purpose or purposes of the largest cisterns remain unclear. The phase 1 and 2 modelling make clear that these cisterns can supply the local population without any significant impact on their volume. Investigating how the wider system responds to the need to fill these cisterns can offer some insight: if diverting water to fill the cisterns causes detrimental impact downstream, it might not have been a regular occurrence, indicating that these cisterns were drawn upon only in emergencies.

To investigate, each of the large cisterns (Mokios, Aetius, Aspar, Basilica, Modestus, Binbirdirek and Philoxenus) was reduced to ~$^1/_8$ of its total volume on 1 January in the model run. The time for the cistern to refill and any discernible impact on the rest of the network was noted. Each cistern was emptied individually and then in combination. Mokios, Aetius, Aspar and Binbirdirek were able to refill without any impact on the rest of the network and their refill times ranged from two months (Aspar) to almost one year (Aetius).[77] The Basilica cistern refills relatively quickly (about 1.5 months) however it has a

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[77] The difference in fill time is down to the valve schedule – Aetius is only open for refilling 6 hours per day whilst Aspar was set to refilling 24 hours per day.

significant impact causing service failures at two downstream cisterns (G6/1 and G6/4) and the Achilles Baths. Cistern G6/1 and the Achilles Baths cistern take significantly longer to recover to pre-filling levels. Filling the Modestus cistern (D5/4) results in multiple service failures for the cisterns (C6/1, D6/3, D6/4, D6/5, D6/6) on the same branch off the main channel. When all the large cisterns are emptied at once, the impact on the system is equivalent to the individual cases – that is, the service failures associated with the filling of the Basilica and Modestus cisterns occur but there appear to be no additional failures caused by the combined filling requirements of the other large cisterns. Again, the conclusion that can be drawn is that generally, the system can cope with the burden of filling the largest cisterns, while the failures associated with filling the Modestus cistern could potentially be prevented by alterations to the management schedule. However, this is not the case for the Basilica cistern because its water source, the Aqueduct of Hadrian, is restricted and in a precarious balance with the demands that is put on it.

## 7.7 Summary

This chapter has presented the agent-based model of the reimagined water supply of Constantinople in the early 6th century. Bringing together the previous work on the physical infrastructure, inflow and demand, the model has demonstrated that not only does each element stand up to scrutiny alone, but can also be combined into a working system. This adds confidence and robustness to the conclusions and assumptions that have been made in the foregoing chapters.

Using NetLogo has allowed a conventional mass-balance model of the distribution network to be incorporated into an agent-based model which allows the population of the city to be represented independently from the water system and the interaction between the two to be studied.

It has been possible to achieve satisfactory performance for all but the most challenging of inflow scenarios – the lower than average flow year (Year 1) and the highly reactive springs. The work undertaken with this model can only be considered preliminary – it has proved the concept of a reimagined system and the benefits of an agent-based approach yet has not thoroughly mined what can be learnt. However, there are a number of inferences that can be drawn:

- The Mokios cistern and Hill Seven could probably have been fed by water from the Halkalı springs.
- In general, the system fed by the Aqueduct of Valens is able to cope with the burden of filling the largest cisterns alongside maintaining supplies elsewhere, suggesting that these cisterns could have had a role beyond being emergency back-ups.
- However, the Aqueduct of Hadrian was finely balanced and alterations to demand levels could cause significant impact, suggesting that the law restricting its use was warranted (*Cod. Just.* 11.42.6, trans. Frier *et al.* 2016).
- The large users at the downstream end of the system – particularly the Baths of Anastasia and Arcadius – were the most vulnerable to drops in water inflow (whether caused by mismanagement or periods of dry weather) and were the most likely of the baths to fail.
- For the cisterns, size definitely matters – the smallest cistern, F7/14, was the most volatile, recording service failures in almost all the phase 1 scenarios and was the only cistern to fail in the phase 2 scenarios.

The management strategy and decisions hugely influence the performance of the system. Undoubtedly there must have been a considerable workforce associated with directing, communicating and monitoring water flows and storage as well as a strategic level of decision makers who were able to do their jobs sufficiently well to merit reports, in literary texts, of abundantly available water. They did this without access to the tools I have used to investigate and reproduce the system – a model that creates a system-wide overview, the ability to run through a year in just over an hour, instant and constant measurements of flow and volume and the ability to explore and experiment with multiple “what if?” scenarios in order to create a management strategy that worked. Whilst it has not been possible to definitively eliminate any of the inflow scenarios, further consideration of this aspect in the next chapter may allow additional conclusions to be made.

# Discussion

Was a merged inflow possible? – spring flow characteristics – some practical considerations on management – the largest cisterns and network interconnections

## 8.1 Introduction

This study seeks to move our understanding of the water supply in Constantinople forward. To do so we have examined the remaining physical evidence from an engineering perspective and developed an agent-based model of a reimagined system. We cannot say that the reimagined system fully represents the original system but, as it has been developed based on the same major constraints imposed by the landscape, the inferences that can be drawn for this system can be considered broadly appropriate for the original system as well.

Now that the preparatory work and modelling of this study have been completed, there are a number of salient points for discussion:

- Firstly, discussed in Section 8.2, the matter of whether the 5th century expansion phase of the Aqueduct of Valens merged with the existing 4th century phase such that the flow entered the city in a single channel, or the channels ran in parallel into the city.
- Secondly, discussed in Section 8.3, there is a great deal of uncertainty about the characteristics of the springs that fed into the Aqueduct of Valens channels. Ruggeri modelled a range of spring flow options (see section 5.3.1) when creating the inflow data used in the model – do the results obtained from the modelling allow us to determine whether any of these options is more likely than the others?
- Thirdly, discussed in Section 8.4, what can be inferred about how the system had to be managed in order to be successful and would it have been possible without the digital overview created in the model?
- Fourthly, discussed in Section 8.5, can anything be surmised about the role of the largest cisterns and the potential interaction of the Aqueduct of Valens and the Aqueduct of Hadrian?

## 8.2 Aqueduct of Valens – a merged or parallel system?

The lack of archaeological evidence of the broader aqueduct (associated with the 5th century expansion) downstream of Kalfaköy leads to the suggestion that the

4th and 5th century phases of the aqueduct may have merged into a single channel (the existing, relatively narrow, 4th century, channel) (Crow, 2012, p. 41).

Merging the aqueducts some distance outside the city is potentially a workable solution – the results of the modelling presented in Chapter 7 indicate that it was technically possible for the inflow from a merged system to support the city, at least on a low *per capita* demand. However, from examining the physical evidence, potential reasons for merging, the practicalities of constructing a merged system, the disadvantages compared with the parallel option and the evidence from the model of the management requirements, I believe that the parallel system is more likely to have been constructed.

### The physical evidence

The possibility of a merged system only really emerges from the lack of evidence of two channels in the furthest downstream section of the aqueduct. However, within the city, we now have the 2-m-wide channel in Baş Müezzin Sokak (see Section 6.4.1) as evidence that a wider, higher capacity channel may have reached the city. But, slightly further downstream of this, the observed channel width reduces: Dalman (1933) reports two channels, 0.63 m wide and 1.76 m high, crossing the Bozdoğan Kemeri at Arch 1. Unfortunately, the western end of the Bozdoğan Kemeri has since been destroyed and only a single blocked-up channel remains visible. This channel measures 0.95 m wide (Crow *et al.* 2008, p. 119).

The fourth century phase of the aqueduct was already longer than any known in the Roman world (205 km with an additional 41 km branch to a spring in Pınarca). It had taken approximately 25 years to construct (Snyder, in preparation). The second phase of the aqueduct was an even larger undertaking. If it continued all the way into the city (*i.e.* a parallel system) its length was approximately 318 km. For a considerable distance between Ballıgerme and Kalfaköy, the two channels run in parallel but at different levels, with the 4th century channel gradually dropping down to the same level as the fifth century channel. Along this part of the route the 5th century work involved the construction of large monumental bridges capable of carrying both channels and cutting off long loops of 4th century channel that crossed valleys much further up, at a point where a small bridge (often single span) was feasible.

The length of the first phase indicates how limited the viable options for water supply were in the region. The desire to construct an even longer, more monumental aqueduct must have been driven by more than just an opportunity to display wealth and power: there must have been a perceived need for more water or more consistent water supplies.

The physical evidence, both inside and outside the city is insufficiently conclusive to inform the debate. The importance of the 5th century aqueduct is clear in its size and scale. This could be argued as a reason for its completion all the way to the city to be seen as a priority. On the other hand, the monumental scale of the project might have proved hubristic and been prematurely curtailed.

### Possible reasons for merging

There are three possible reasons for ending up with a system that merged some distance from the city: the project ran out of money or materials; the project ran out of time and there was an urgent need for more water in the city; or, the flow characteristics produced by the merging were perceived as better and easier to manage than the more variable flow produced by a fully parallel system.

There would be a significant saving in not continuing the 5th century channel all the way to the city – 138 km of channel (Ruggeri 2017) and associated bridges would not need to be built. However, although the construction would undoubtedly have been expensive, there is little to suggest a sudden problem with finances. Construction within the city continued, including investment in the water supply in the form of the major cisterns.

Given the lengthy construction times estimated by Snyder (in preparation) a situation may have arisen where the need for more water in the city became critical and it was judged necessary to sidestep a decade or more of construction work. A merging of the channels would have increased the flow arriving at the city when compared to the 4th century channel conveying only the 4th century springs (Danamandıra and Pınarca) but provided less than could be conveyed in a parallel system. It may have been intended as a short-term measure that would enable the remainder of the 5th century channel to be constructed at a more leisurely pace. Perhaps once the merged system was in place, it was deemed sufficient for the needs of the city and the growing population and the planned construction of the remainder of the 5th century was not completed. This is a reasonable line of argument but as it is based solely on a lack of evidence, it should not be given much weight.

The final reason for creating a merged system would be in order to engineer a particular set of flow conditions in the city. Referring back to the inflow graphs in Chapter 5 (Figures 5.5 – 5.8), it is clear that (with the exception of the drier than average Year 1) in the merged cases the inflow into the city is a steady figure of about 0.7 $m^3/s$ for much of the year. This might be perceived as an advantage – a largely predictable inflow and a clear signal when there was deviation from the normal inflow. However, it does not follow that this situation would be easier to manage than the parallel inflow, because that consistency and predictability would be bought at the expense of volume. Further, to transport water tapped by the 5th century phase of the aqueduct up to 180 km and then lose everything above the capacity of the narrower channel at the merge point seems perverse. In a typical year the merged system would have spilled about 1/3 of the total volume it could have carried as a parallel system (see Figure 5.4 in Section 5.3.1). Would such a profligate use of a scarce resource be acceptable when it offers no clear advantage and removes the opportunities to stock up on water created by conveying storm peaks into the city?

### Practicalities of constructing a merged system

A minor, but nevertheless important, factor to consider is how the two channels could be joined while still maintaining a water inflow into the city.[78] A chamber constructed across the 4th century channel, with the 5th century channel entering as an additional inflow is the likeliest solution. As discussed above, the merging would result in considerable overflow, and this would have to be carefully managed and monitored to prevent erosion of the hill slope, which could lead to the channels being undermined.

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[78] At this stage, the city had not yet built a significant number of cisterns so would have had little in the way of reserves, making a constant inflow important.

### The modelling evidence

The modelling presented in Chapter 7 offers an extra perspective to the argument. Under the phase 1 modelling, with its management settings appropriate for the most generous inflow scenario, it is possible to scrutinise the comparable merged and parallel scenarios by the number of failures occurring for each cistern. The merged scenarios generally perform slightly worse than their parallel equivalents. There are 104 failure pairs available for comparison – directly comparing the number of failures for a cistern in the merged and parallel cases for the same inflow scenario. For example, from Table 7.3, Cistern E6/4 fails for two days longer in the HRY1 (highly-reactive Year 1) merged case than in the HRY1 parallel case, so we can say that this cistern performs slightly better in the parallel case. Of the 104 pairs, 16 are neutral (there is no difference between merged and parallel cases), 64 show an improvement in the parallel case and 24 show an improvement in the merged case.

A note of caution is required here. Many of the pairs compared show only a small difference (one or two more days of service failure) between the merged and parallel. In these cases, it is difficult to determine whether that improvement has been caused by the differences in overall inflow as there is a degree of randomness within the model, both in the positioning of the population during the model set-up and their daily selection of which cistern to collect water from. These factors could account for the smaller differences between cases. However, for a number of cisterns the evidence is clearer – there is a large deterioration in performance between the parallel and merged cases for both G7/3 and F7/8, and to a lesser but still notable extent for F8/11. The position of these cisterns is noteworthy – all are at the downstream ends of branches; they are some of the most peripheral points on the network. These are the cisterns that are the last to take their share of the available water, so they are the most vulnerable to a decline in water availability.

In the phase 1 modelling the standard to be achieved was not demanding: once successful performance was reached for the ParNRY2 (Parallel non-reactive Year 2) scenario, no further improvements were made. As a result, failures in the other scenarios are to be expected – they all have less water and/or have much more variable inflow. The management rules are sub-optimal for these cases. Failures occur in both the merged and parallel scenarios, but as can be seen by the summary in Table 8.1 the parallel cases do better than merged, particularly in the reactive spring cases. What the parallel cases have that the merged cases lack are the periods of higher flows associated with storm peaks. These serve to quickly top-up cisterns enabling rapid recovery from failures that occur during dry periods and preventing extended periods of service failure. In the merged cases, with less water generally available, the peripheral cisterns struggle to recover once empty and are prone to longer periods of failure. A similar situation can be observed in the phase 1 results for bath performance, detailed in Table 7.4 and summarised in Table 8.1. The Baths of Anastasia are at the end of the Aqueduct of Valens and show a marked deterioration in performance in the merged cases. The parallel inflow offers leeway that the merged inflow simply cannot. The phase 2 modelling demonstrated that it was possible to have successful performance for the merged flow, but it is difficult and requires tight control of the distribution decisions. The practicalities of achieving such control in the real world are explored in Section 8.4.

## 8.3 Spring flow characteristics – non-reactive, moderately-reactive and highly-reactive

The daily inflows were developed by F. Ruggeri specifically for use in my model because it needed a high degree of granularity in the data to realistically investigate how the system would have managed its water storage. As so little is known of the characteristics of the springs that fed the aqueducts, Ruggeri created a range of possible inflows which reflected three different spring characterisations: non-reactive, moderately-reactive and highly-reactive. Now that those inflows have been incorporated into the model of the system, can we use the performance of the system to examine the likelihood of each inflow?

### Model results

Working with the models it is clear that the highly reactive flow was the most difficult to work with, the most challenging inflow for which to manage a satisfactory performance. On the surface, this is unsurprising – the highly-reactive springs are characterised by flows with extreme peaks but also by extreme troughs, a very low base flow from the springs and a rapid peak in response to rainfall events. Any period of dryness, even a few days, leads to cisterns drawing down their storage and leaving them more vulnerable to service failure. The moderately-reactive springs work on similar principles but have a higher base flow so their low points are not so severe. The non-reactive spring inflow, in contrast to the other two, does not have the peaks, consisting of twelve monthly values. It consistently provides a higher total volume (see Figure 5.4) and performs better than the other two spring characterisations.

Table 8.1: Summary of phase 1 modelling performance

| | Parallel | | Merged | |
|---|---|---|---|---|
| | Total cistern fails (days) | Total Bath fails (days) | Total cistern fails (days) | Total Bath fails (days) |
| Non-Reactive | | | | |
| Year 1 | 451 | 158 | 454 | 162.5 |
| Year 2 | 0 | 0 | 0 | 0 |
| Year 3 | 0 | 0 | 0 | 0 |
| Year 4 | 0 | 0 | 0 | 0 |
| Moderately-Reactive | | | | |
| Year 1 | 605 | 227.5 | 830 | 299 |
| Year 2 | 30 | 31 | 446 | 167 |
| Year 3 | 9 | 28.5 | 518 | 162 |
| Year 4 | 32 | 38.5 | 385 | 161 |
| Highly-Reactive | | | | |
| Year 1 | 1055 | 411.5 | 1223 | 479 |
| Year 2 | 174 | 101 | 621 | 235.5 |
| Year 3 | 342 | 128.5 | 720 | 252.5 |
| Year 4 | 302 | 141.5 | 773 | 517 |

As the measurements used to judge the model are all about measuring negative performance, rather than positive, it is difficult to make comparisons and conclusions on the phase 2 models, because almost all of them work satisfactorily (except the highly-reactive Year 1 inflow). However, the phase 1 modelling offers more potential for comparison. Table 8.1 and Figure 8.1 are generalised versions of the data previously presented in Tables 7.3 and 7.4. From these it is clear that the non-reactive inflows have the best system performance: for Years 2, 3 and 4 there are no failures and fewer failures occur for Year 1 than in the moderately-reactive and highly-reactive inflows. The number of failures increase with the reactivity of the spring flow. The two reactive inflows also show a marked deterioration between the parallel and merged scenarios that is not apparent in the non-reactive case.[79]

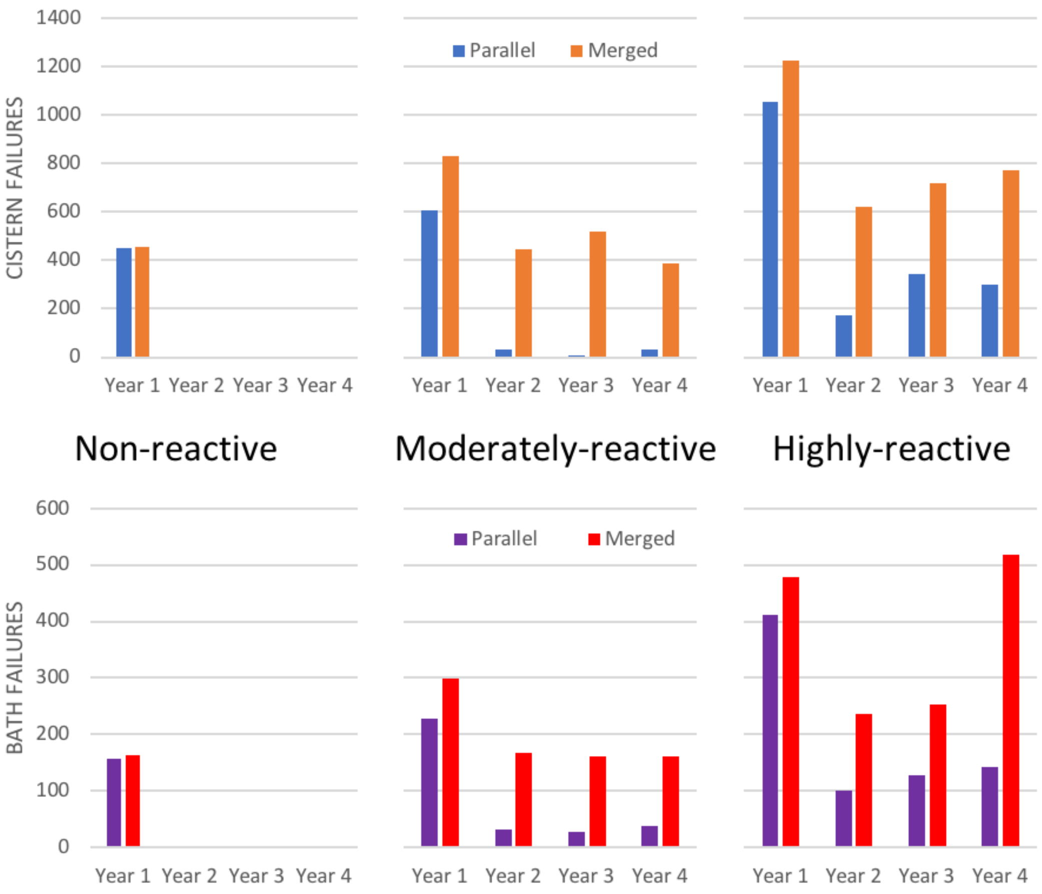

Figure 8.1: Summarised results for the phase 1 modelling

### Cistern purpose – managing variable inflow

The performance of the system in the non-reactive case leads to an interesting question: if the inflow was as smooth and steady as in the non-reactive case, would the cisterns actually be required? At first glance, it would appear that a non-reactive flow could make the cisterns redundant.

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[79] Although, to be accurate, we must note that the difference in number of failures in the parallel and merged cases tend to be lowest for Year 1 – probably because the generally low volume of water is a significant factor leading to failure. Figure 5.4 illustrates the small differences in available volume between parallel and merged cases for Year 1.

Almost two-thirds of the cisterns in the city held less than two weeks' worth of supplies for their typical daily users.[80] The largest cisterns are exceptions, with huge storage volumes providing multiple years' worth of supply for their typical daily users. But most cisterns seem designed to allow them to continue providing water during relatively brief dry spells, which would not occur in the non-reactive spring scenarios.

Examining the inflow data, it is possible to identify the longest periods of reduced flow in each inflow scenario. For the highly-reactive springs there is a 21-day drier period[81] in Year 2, a 19-day drier period in Year 3 and a 24-day drier period in Year 4. For the moderately-reactive springs the maximum lengths of the drier periods were shorter, at 15, 17 and 19 days for Years 2, 3 and 4 respectively. There were no drier periods for the non-reactive springs for these years. The drier periods in Year 1, the year representing a drier than average year, are much longer: for the non-reactive spring 92 days, moderately-reactive springs 80 days, and highly-reactive 81 days. During the drier periods, the system must rely more on the storage of the cisterns to allow normal water consumption to continue. As can be seen in the phase 2 modelling it is possible to manage the distribution so that normal consumption is maintained throughout the year – the storage within the cisterns successfully bridges the drier periods. The exception is the HRY1 scenario where the extended dry period over the summer and the fractured periods of wet and dry on either side of it are too much for the system to cope with.

### Cistern purpose – maximising daily availability

If the flow was smooth and not prone to drier periods (as in the non-reactive spring case) what would the purpose of the cisterns be? Cisterns might be required to act as a buffer if the demand is higher than the real time delivery rate. If the amount needed during the collection hours (for example, the model used 6 am – 9 pm) is greater than the amount delivered during that time period

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[80] Taken from the people-counting monitor within the model, the average number of daily visitors across the full length of the model and assuming maximum capacity of the cistern.

[81] Drier days were taken as having a flow below 0.65 m$^3$/s which was the typical flow when the merged system was running full. Drier periods consisted of consecutive drier days.

but equal to or less than the amount delivered over 24 hours, the cistern could store the additional night-time flow for use during the day.

This daily-balancing is quite different to the managing inflow volatility that was described above. It implies that the supply and demand were almost equal. However, the feasibility of this strategy over the longer-term needs to be examined. If this was the driver, then the inflow and demand must have been fairly evenly balanced at the time of construction. But that does not tally with the staggered development of cisterns and the long-term feasibility of the system. Cisterns were being constructed throughout the Byzantine period and the early development of the system took decades. If there was already a need for cisterns to balance supply and demand at the start of this process, the addition of extra cisterns would not have counteracted the steady increase in population and the concomitant increase in demand that occurred during the 5th and 6th centuries. And there would be no need to continue building cisterns in the late 6th and early 7th centuries[82] when population numbers were still recovering from the devastating impact of the plague.[83] Overall, the argument appears to be stronger for cisterns supporting a fluctuating inflow rather than to manage a close correspondence between inflow and demand. Therefore, the inflow from the non-reactive spring can be considered unlikely to represent the actual inflow. There was probably some degree of fluctuation in the inflow (in addition to a slower and more predictable seasonal change) and it was this tendency to fluctuate that led to cisterns being constructed throughout the city. The degree of fluctuation and therefore the reactivity of the springs to rainfall is still uncertain but the modelling points towards a high degree of fluctuation being considerably more difficult to manage.

## 8.4 Successful management of the water supply

Successful water management is not simply a case of having enough water to go around, it is also necessary to get it to where it is needed, when it is needed. To

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[82] Such as the cistern at the Bronze Tetrapylon and the cistern of Bonus (see Crow *et al.* 2008, p. 15 for a fuller list of cisterns with known construction dates).

[83] There are reports that the number of dead bodies was so overwhelming that the cemeteries quickly became full and bodies were placed in cisterns – presumably these were empty and may have taken some time to recommission.

do that, there must have been an organisation responsible for taking the actions necessary for the distribution of water, not only on a daily basis – adjusting sliding gates, placing and removing stoppers, monitoring of cistern water levels, but also sporadic but critical decisions such as the diversion of flows into the large cisterns at the upstream end of the network, and longer term planning such as the siting and construction of new cisterns and fountains. We know little of this organisation and its workforce: a law of the late 5th century (*Cod. Just.* 11.42.10)  calls for "inspectors and guardians of water" to be branded on their hands so that their work is not interfered with. Crow (2012) traces the evidence of administrators associated with managing the urban water supply from the initial construction period through to the 11th century.

### What would the water team need to do?

While changing the flow from one pipe to another in the model merely involves changing a number in a table, in reality physical work was involved. It would be necessary to set gate positions in control mechanisms throughout the network. As was the case in the model, the setting of gates is likely to have been partly governed by a daily schedule, assigning flow to particular branches and cisterns at certain times and partly by monitoring the water level within cisterns and evaluating the need for more or less inflow. There were 78 nodes used within the model to distribute water to 87 cisterns. Some of these nodes acted as simple bifurcation points, not requiring visits for changing gate settings, but the rest would need to be visited, sometimes many times a day, to open and close the relevant gates.

### Managing without the digital overview

At this stage it is important to remember that while our modern tools can reveal what the hard infrastructure system could potentially do, this actually tells us very little. The hard system was governed by a soft system – the people operating it. And it is only by realistically considering their actions that we can build up a picture of how and how well the system they were in charge of was able to perform.

One of the major advantages of the computer model is that it allows rapid experimentation: alterations to valve schedules or adding feedback loops takes only a few minutes and to model the full year of inflow data takes just over an hour. The results are automatically recorded and after a few hours of processing can be examined. The live plotting within the model (see Figure 7.5) provides an even quicker view of the impact of changes that had been made. Using these tools it was straightforward to tweak the model towards successful operation. Even being able to quantify the total inflow, demand and storage allowed me to know that it was worth continuing to tweak the management rules, that there was a probable solution. This does not reflect the tools or the processes available to the Byzantines, who could only work on a real system, in real time, and whose capacity to record and analyse the ramifications of their changes was unknown.

It was not possible to successfully manage the merged flow scenarios just using alterations to the daily valve schedule. In addition to the 149 daily changes at valve nodes, feedback loops monitored the water level in 76 cisterns and made alterations to pipe flows and opening and closing times based on the results of that monitoring. Some of the feedback loops were relatively simple, usually where a cistern was connected to the main line, where the normal valve schedule could be temporarily suspended when the cistern was sufficiently full and reinstated when the volume stored within the cistern dropped below a particular level. Twenty-three of the monitoring tasks were more complex, managing the water flow in an entire branch based on the water levels in multiple cisterns so that if some cisterns are full and others are not, the flow entering the branch is reduced to be appropriate for the cisterns still requiring water, preventing unnecessary waste. This is a straightforward exercise in the model, where volumes and flows can be monitored and altered instantly and the analysis of the more complex situations is automated. When transferred into the Byzantine period, where variable flow was difficult to gauge, precise time-keeping less accessible, systems-wide analysis a potentially unknown concept, and individual cistern volumes would be monitored by people and then communicated – presumably by runners – to those with the authority to change control settings, there seems little likelihood that an inflow scenario as precarious as the merged (reactive) one could have been successfully managed.

## 8.5 The largest cisterns and interconnection in the distribution network

Having completed the detailed analysis of the available infrastructure-related evidence and with the experience and results of modelling the reimagined system, there are further points to be discussed. The potential interconnection between the two systems has not yet been modelled but the results of the separate systems point towards reasons and potential points of interconnection that encompass potential purposes for the largest cisterns and help improve performance at several baths and the capacity and resilience of the Aqueduct of Hadrian.

### The two systems

The Aqueduct of Hadrian had such a limited flow that there was a restriction, established by a late-4th century law, on who could access the water it carried (*Cod. Just* 11.42.6). Yet by the mid-6th century, it was possible to add the Basilica cistern, with over 80,000 $m^3$ of storage to this aqueduct. The modelling of the Aqueduct of Hadrian had to be based on relatively basic data and a broad assumption. A daily yield value from the Ottoman Kırkçeşme Aqueduct that replaced the Aqueduct of Hadrian in the 16th century has been used as a uniform inflow figure across the year. Nevertheless, the results of the model indicate that this assumption reflects the type of situation that led to the law restricting water use. The flow in the Aqueduct of Hadrian is able to support the small number of users that draw its water, including the Great Palace, Zeuxippos Baths, Basilica cistern and Arcadius Baths but only if the Basilica cistern starts the model full. If the Basilica cistern has to fill up using the Aqueduct of Hadrian inflow, there are service failures in the downstream cisterns and baths. If the *per capita* demand is increased from 30 litres/day to 50 litres/day, there are service failures in cisterns and baths. The system is very finely balanced: fluctuations in either the supply-side or the demand-side are likely to cause difficulties in achieving satisfactory performance.

The Aqueduct of Valens, on the other hand, has a significant inflow but an extensive network to distribute that flow across. The construction of large open-air cisterns[84] at the upstream end of the distribution network gives the opportunity to store large volumes of water within the city, but because of the location of the cisterns at the upstream periphery of the city, the decision to divert and store water must be made before others have had a chance to use the water. Fear of accidentally depriving the downstream end of the network could lead to excess water being passed forward. The utility of such storage as an emergency supply is hampered by its location out on the edge of the city and distant from the population centres. In general, location relative to the main aqueduct is important, with water security (or the likelihood that you will have access to the water you need) decreasing as you move downstream through the system. The users at the most peripheral downstream points are the most likely to suffer shortages as everyone upstream has the opportunity to take water before they do. On the Aqueduct of Valens, one of the last water users to receive water are the Baths of Anastasia, located on the southern slopes of the city in Region IX. As a result, these are the baths most prone to failure.

### Benefits of connecting the two systems

Connecting the two aqueducts would have benefits for both the systems that they serve. From the modelling it is clear that increasing the volume of water available within the Aqueduct of Hadrian would make its management less precarious and having access to additional water is essential for tasks such as the extended filling of the Basilica cistern. Additional flow would also likely be essential for the operation of the suggested northern branch of the Aqueduct of Hadrian that splits from the main aqueduct at the Tezgahçılar Kubbesi structure and feed the northern slope of Hill Three. Although this branch has been drawn on maps (see Map 6.8) it was not included in the model as there was insufficient inflow from the Aqueduct of Hadrian to support additional water users.

Interconnection of the systems would also provide a way of transporting water from the open-air cisterns on the periphery into the heart of the city. The (assumed) location of the Baths of Anastasia sits below the route of the

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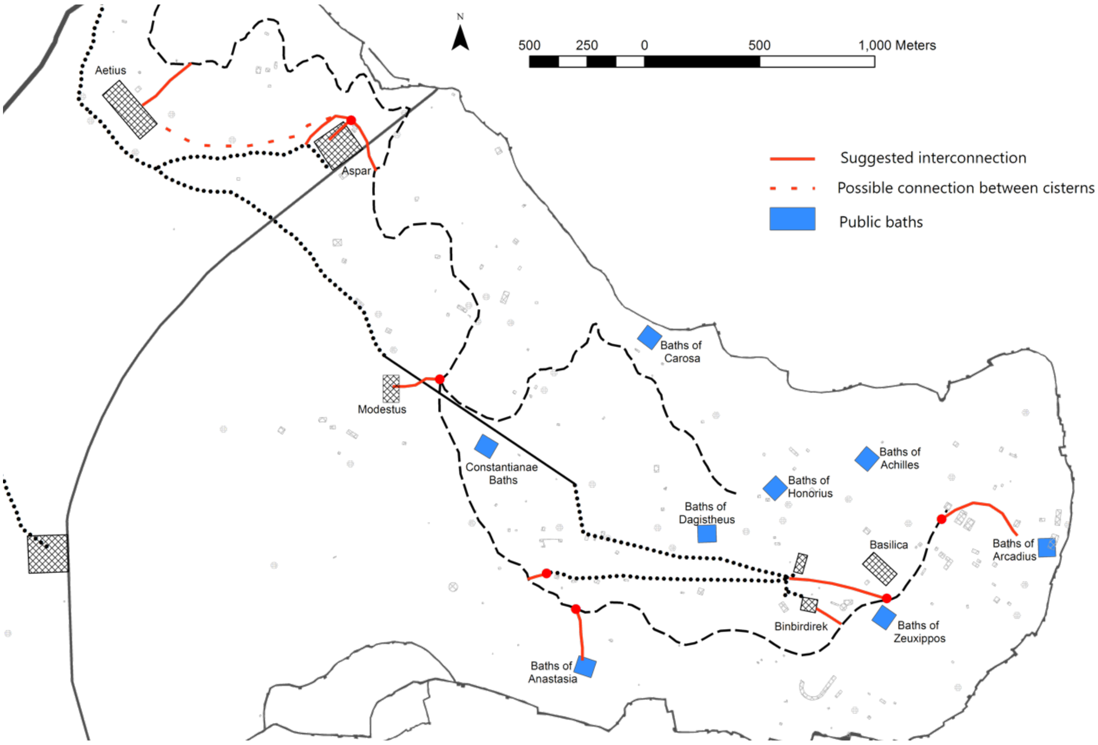
[84] At least two: Aspar and Aetius but we could also include Modestus and possibly Arcadiaca. Mokios is the largest of all but its position on Hill Seven is isolated from the rest of the network and as discussed in Chapter Seven, it may have been fed by a source other than the Aqueduct of Valens.

Aqueduct of Hadrian, so it is possible that it could be connected to the Aqueduct of Hadrian boosted by water from the Aqueduct of Valens. This would turn the Baths of Anastasia from one of the last, and therefore most vulnerable, water users, into one of the first, with a more robust and secure supply.

Such interconnection is, at least on the surface, compatible with the more challenging inflow conditions of a merged system. Indeed, it might be the only way to make a merged system work with realistic management capability. However, further investigation would be required, to study the sustainability of filling and using the open-air cisterns over the longer term with the more limited flow.

### Possible connection points

The control mechanism discussed in Section 6.5.1, Aspar 1, has already been identified as a potential connection point between the Aqueduct of Valens and the Aqueduct of Hadrian (see the discussion in Section 6.2.3). Clearly linked with the Aspar cistern the inflow into the structure from the northeast might be associated with a direct link to the Aqueduct of Valens, enabling the cistern to be bypassed, or might be an outlet channel from the Aetius cistern which is similarly well placed to feed into the Aqueduct of Hadrian. No other strong evidence of connection between the two systems has been found but, as shown in Map 8.1, there are multiple locations where the aqueducts cross and could interact. In addition to Aspar and Aetius, the Modestus cistern in its assumed location at Saraçhane could be an even earlier link between the two systems. It is located halfway down the slope of Hill Four and in relatively close proximity to the Tezgahçılar Kubbesi structure, which might have served as an inflow point as well as a junction in its earlier incarnation as part of the Byzantine system. If the Baths of Anastasia were fed or supplemented by the Aqueduct of Hadrian there would need to be an outflow connection.



Map 8.1: Possible interconnections between the Aqueduct of Valens and the Aqueduct of Hadrian.

Other connection points are possible. Where I have assumed the Valens channel doubles back along the south side of the Mese, a connection at its terminal point could capture any overflow and direct it into the Aqueduct of Hadrian. Another potential connection point is between Hill Two and Hill One. As discussed in Section 6.6.1, the Aqueduct of Valens is the most likely source of water for the cisterns on and around Hill One as well as the Baths of Arcadius. However, the route by which the water from the Aqueduct of Valens reached these areas remains uncertain. One possibility is that part of the Aqueduct of Valens flow combined with the Aqueduct of Hadrian and was tunnelled beneath and through Hill One to be lifted up to its peak and to provide flow on the other side – this option reflects what is seen in the later Ottoman system (see Figure 6.16 and Map 6.11).

## 8.6 Summary

This chapter has considered the evidence and possible interpretations of four main questions. Firstly, when considering whether the Aqueduct of Valens had a merged or parallel arrangement, it is reasonable to assume that maximising available inflow would be the aim, as there are no discernible advantages to voluntarily spilling one-third of your potential water supply. Whilst the merged system remains technically possible, the parallel system is the likelier arrangement.

Second, the characteristics of the spring inflow were considered by comparing the results of the three assumed inflows – non-reactive, moderately-reactive and highly-reactive – and reviewing the inflows with respect to the cisterns and their potential purposes. Although the non-reactive springs produced the best performance overall, it is difficult to make a convincing argument for the need for cisterns with a smooth and slow-changing inflow. In contrast, the typical flow pattern of the reactive springs with periods of low flow between rainfall events provides a logical argument for the cisterns and provide an explanation for the size of the cisterns, with most providing enough storage to balance the short periods of lower flow.

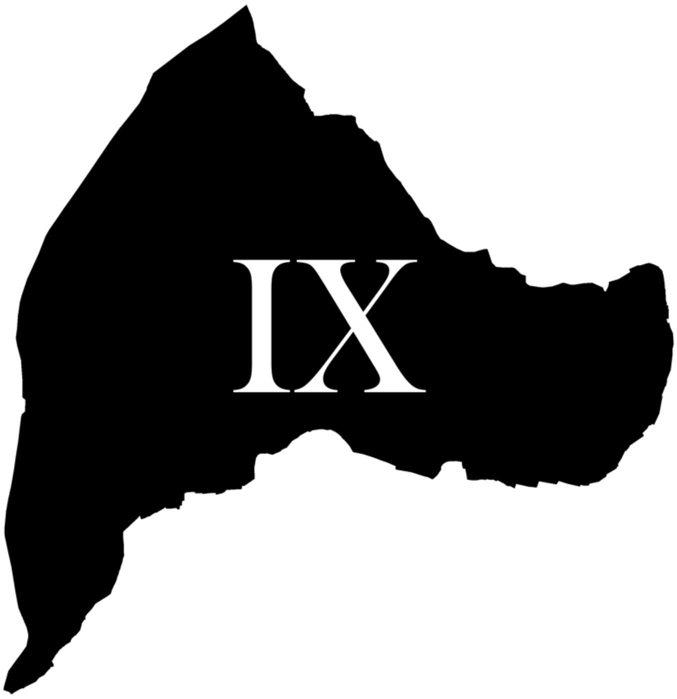
The third discussion, concerning the management that would be required to successfully manage the water distribution network is closely linked to all the other questions. In some ways it is also one of the most difficult to address as we know so little of the water system managers and how they worked. We have clear evidence of the success and longevity of the system so it can be tempting to assign high levels of sophistication and competence to the managers and over-claim on how well they could have managed a limited flow. With access to modern tools it is possible to satisfactorily manage the merged inflow scenarios, but without those modern tools it is far less likely that managing a restricted inflow was possible.

The final discussion, on the possible interconnection of the two aqueducts within the city, moved beyond what had been modelled and considered the systems and potential benefits holistically. There appear to be clear benefits to interconnecting the systems by permitting the easy movement of stored water and improving flow to a number of vulnerable users.

All the questions, although considered separately, are interrelated and interdependent. The option that emerges from this discussion as the most likely is a parallel inflow arrangement, conveying water from springs with some degree of reactivity that leads to a fluctuating water level and a strong driver for the continued construction of cisterns. Such a flow would be more likely to be within the capabilities of the people managing the water flow to manage successfully. Further resilience is likely to have been added by interconnecting the two aqueducts, allowing the storage within the largest cisterns to be used to improve the performance of the overall system as well as act as a back-up for times of drought.

# Conclusions

Closing the loop: achievements and outcomes, contribution to knowledge, beneficiaries – limitations: the necessary rough sketch – future work and reflections



“We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.”

T.S. Eliot, Four Quartets

## 9.1 Introduction

Before this research study began, relatively little was understood of the water supply in Constantinople, particularly within the walls of the city. The main focus of Crow *et al.* (2008) was to report on the field work that mapped and unravelled the long aqueducts in Thrace, although time was also spent on the water supply inside the city walls. They were able to firmly establish that the Bozdoğan Kemeri, the most visible bit of the water supply system still remaining, belonged to the Aqueduct of Valens. They also mapped 159 cisterns, collating the evidence in a bibliographic concordance. The evidence was not so clear on the routes of the aqueducts, particularly the Aqueduct of Hadrian, but attempts were made to project potential routes. While a small group of scholars were aware that the number of cisterns within the city was substantial, the wider academic community was still reporting that there were only 70 cisterns (for example Mays 2014). Other useful studies have been conducted on the cisterns, particularly Altuğ (2013), but these focused largely on archaeological aspects of the individual structures. With the available data fragmented, and the potential for more evidence limited to serendipitous finds associated with construction work, the only way to move the understanding of the water supply forward is to take a radically different perspective.

Engineers with a technical background in modern water supply are well placed to take such a radically different perspective. Being able to envisage the water supply system in its entirety should move understanding further forward than considering each cistern in isolation. Yet when engineers have become involved in archaeological work previously, it has often been in the role of engineer-as-analyst or using positivist principles. On these occasions the studies had to be limited to the small fragments of evidence which had enough evidence to support modern analysis techniques such as computational fluid dynamics modelling (see Section 3.4, particularly Sections 3.4.3 and 3.4.4). Usefully relating these results back to the period, or for archaeologists and historians to interpret, was sometimes difficult because there was a tendency to measure and evaluate using modern concepts (such as efficiency). It is only when researchers have consciously shed the modern viewpoint and taken a wider perspective, bringing in consideration of construction choices and techniques that were available at the time, that they are able to produce more interesting and useful insights.

Engineering, particularly outwith the bounds of (typical) academic research, offers a wide range of approaches for the engineer to choose from. In this study the skills of an engineer as designer are what are needed to move beyond isolated fragments of evidence to an understanding of a whole, functional system. What makes engineering design a suitable tool for this area of research is its two-fold nature: working towards a goal (in this case a complete model of the system) also generates detailed knowledge of the subject.

The reimagining of the water supply was driven by a key piece of knowledge: the water supply worked, and worked for many centuries. That fact, combined with the fragments of physical and literary evidence, the largely unchanged landscape and the fundamental physical laws governing gravity-fed water systems, are enough to start filling in the information necessary to create a complete system.

The core work in reimagining the water supply system has been developing an understanding of the physical infrastructure of the distribution system. Although the two most recent and comprehensive studies appeared to agree that there were about 159 cisterns in the city, close examination of the available data showed that there were actually 209 with the real possibility of more (see Section 6.2). An evaluation of the aqueduct routes in previous studies highlighted flaws – conflicts with the basic tenet that water flows downhill – and inconsistencies with newly available evidence. Alternative routes were designed that tied together the available evidence, provided a consistently downhill route and were shorter and more straightforward to construct than the previous proposals (see Sections 6.3 and 6.4). Having established the number and spread of cisterns and the locations of the aqueducts, it was possible to create a network delivering water from the aqueduct channels to the cisterns for collection by the public.

Consideration has also been given to what occurs at either end of this physical infrastructure. At the upstream end, quantifying and characterising the water source defines the water available to distribute and helps to indicate the purpose of the cisterns (see Sections 5.3 and 8.3). At the downstream end, developing even a basic model of water consumption (see Section 5.4) has enabled the distribution network to move from a static artefact to a system with a quantifiable purpose.

The combination of the physical infrastructure, inflow data and demand assumptions in an agent-based model demonstrate that the decisions and assumptions made within each element work together and allow a fourth element, management, to be considered.

The agent-based model of the system enables consideration of a dynamic system and the exploration of a number of “what if?” scenarios. This exploration concludes that the cistern-based distribution system probably developed because of fluctuations in the aqueduct inflow. It may have been possible for the city to use a merged arrangement on the Aqueduct of Valens inflow but that the burden of pro-active management required to make it successful suggests that a parallel arrangement is more likely. There was likely to be an interconnection between the two main aqueducts, which would have enabled the use of water stored in the largest open-air cisterns.

## 9.2 Key outcomes and contribution

The aim of this study, stated in Chapter One, was to investigate whether and how an engineering approach could transform our understanding of the archaeological evidence of the water supply system of Constantinople. This aim has clearly been achieved. This study demonstrates that an engineering approach is a valuable method that has both moved the understanding of the water supply forward and prepared the way for further study and investigation. This study makes a contribution to knowledge by generating a new understanding of the elements and complexity of the water supply infrastructure in Constantinople. Furthermore, the study demonstrates that the methodological approach of engineering design is suitable as a means of inquiry in this case.

From an archaeological perspective, the methodology used in this study – considering the infrastructure as a whole and using engineering design to place the known elements within an imagined but plausible working system – was an effective way of dealing with the fragmented data available. This fragmentation of data is typical of many archaeological sites and the methodology used in this study could be adapted to suit other archaeological studies of water and drainage infrastructure and might be of some use in studies of other forms of infrastructure. The level of data relating to Roman and Byzantine water infrastructure systems varies widely, but the approach used in this study could provide insight into other cities with evidence of complex water infrastructure, such as Rome, Ephesus, Petra and Thessaloniki. A specific contribution for engineers working in archaeological contexts is the positioning of the archaeologist or archaeological community as client. This framing helps to ensure outcomes and contributions that are of use beyond engineering communities.

The key outcomes and their contribution to our knowledge of the water supply system are detailed here:

- An increase in the number of known cisterns in Constantinople's main peninsula by almost 1/3 from 159 to 209. This contributes to our understanding of the coverage of water infrastructure across the city. The updated list in Appendix B supersedes the bibliographical concordance in Crow *et al.* (2008) and complements Altuğ's (2013) catalogue of cisterns derived from archaeological reports.
- A basic model of water demand across the city that incorporates a model of population density in the 6th century. The population density is a refinement of Jacoby (1961) and the proposed water demand model is the first study of this kind for Constantinople.
- Proposed routes for the Aqueduct of Hadrian and Aqueduct of Valens within the city walls. This work contributes to knowledge by disproving previous proposals, and creating a new model of the aqueducts that supersedes Crow *et al.* (2008, Map 12).
- A reimagined distribution system for the mid-6th century, connecting aqueducts and cisterns and assuming the presence of control

mechanisms. This is the first time that the remains of Constantinople's water distribution network have been synthesized into a complete network.

- An agent-based model that combines the reimagined distribution system and the water demand model with the aqueduct inflow data developed by Francesca Ruggeri, enabling exploration of the system and its management. Its contribution to knowledge lies in making visible the complexity of management required to successfully operate the water system for different inflow scenarios. It is also a tool for further research into the water supply and population of Constantinople.

- Although no evidence has been discovered of two phases of aqueduct channel downstream of Kalfaköy, this research suggests it is more likely that the Aqueduct of Valens operated a parallel system comprising the 4th and 5th century phase channels than a merged system in which the 5th century channel flows into the 4th century channel.

- This research suggests a credible explanation for the widespread use of cisterns within the city. It is likely that there was some degree of fluctuation in the inflow from the Aqueduct of Valens, related to rainfall events in the spring catchments and the cisterns of the city could have been a means of managing such fluctuations.

- It is now clear that satisfactory performance of the water distribution system was dependent on a coordinated management effort. A sizeable workforce would be needed to monitor water levels within cisterns and open and close the control gates that must have been used to direct water around the system. In addition to these routine tasks, more strategic decision making would have governed the diversion of water into (and out of) the largest cisterns.

- This research indicates that it is likely that within the city there was interconnection between the Aqueduct of Valens and the Aqueduct of Hadrian. Interconnection would improve the performance in more vulnerable parts of the network and provide a method of moving water out of longer-term storage in the largest cisterns.

All of these contributions relate directly to Constantinople's water supply but stepping back, perhaps the most useful and transferrable contribution is that this study has added to our knowledge of Constantinople in a way that has not been done before. It has demonstrated that an engineering design approach is a fruitful research method for this type of question.

### 9.2.1 Beneficiaries

In Chapter One, three main beneficiaries were identified. Firstly, and most evidently, are scholars working on Byzantine Constantinople. This study explores a key piece of infrastructure within the city that connects not just all parts of the city and its society but is also a common thread present throughout Byzantine Constantinople's long history. This study offers insights into population density and demonstrates the need for a large, organised workforce to manage the distribution of water.

Secondly, the interested public including the residents of and visitors to Istanbul. Some parts of the water supply are part of Istanbul's range of tourist attractions. This study helps to reveal the complexity of what was achieved in Byzantine Constantinople and provides interesting context for the Basilica and Binbirdirek cisterns and the Bozdoğan Kemeri. Through the wider Leverhulme project, information from this study is being communicated to the general public through a bilingual website and has provided background for a BBC documentary on Istanbul.[85]

Finally the engineering research community can benefit from this project as an example of working successfully across disciplines and particularly as an indication that engineering researchers should not shy away from engineering design as a means of enquiry in a research setting. For engineers and technologists who work in archaeological and historical settings it is worth noting that although Smith (2007) warned that "there is a distinct limit to how

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[85] http://byzantinewater.shca.ed.ac.uk/ The BBC documentary Invisible Istanbul is scheduled for broadcast in summer 2018.

far retrospective analysis can properly substitute deficiencies in conventional evidence" that limit may be further out than we, or Smith, thought. It is possible to step beyond conventional evidence and engineering approaches can make that action legitimate and worthwhile.

## 9.3 Limitations

This study has developed the first coherent picture of the water distribution system, its inflow and end use. It was developed from a situation where little was known about the water supply and it should be understood within that context. This first attempt at a complete picture is only a rough sketch and, as such, there are restrictions on how closely it can represent the reality of the water supply system. Reasonable and considered assumptions have been made where evidence is not available, but those assumptions, which have been based on my professional judgement as an engineer, must be recognised as a potential source of bias. Just as I was able to identify a tendency to supply a hydraulic explanation for every design decision in Ortloff's work (see Section 3.4.4), others may be able to offer alternative interpretations or take issue with the assumptions and decisions made. Nevertheless, it is only by first creating a rough sketch that new detail can be added. This research, though limited, provides a platform for others to scrutinise and work from.

## 9.4 Future work suggestions

As discussed in the previous sections, the work and model presented in this study are a mapping of the territory that should provide a platform for future work on the water supply in Constantinople, while the engineering approach employed could be applied to other sites. As the first attempt to create an understanding of the system as a whole – inflow, distribution, management and use – there have inevitably been some assumptions made and further consideration, investigation and refinement of any of these aspects would be of benefit. There are a number of areas of potential further investigation:

- Assumptions made on cisterns of unknown volume. Within this model, all cisterns of unknown volume were assumed to have 1000 $m^3$ of storage. Investigating how varying this figure, or applying a distribution of storage volumes impacts on the overall performance of the system would provide further insight on the role of cistern size and location on the performance of the network.

- The demand model used is limited and would benefit from further development. There are a number of ways that the demand model could be improved that would provide a more nuanced understanding of the water system and its management requirements. Firstly, developing a more realistic distribution of water use throughout the day would enable investigation of the system's capacity to cope with peak demand. Secondly, studying a range of values for the distributed daily demand could identify the maximum water use that the supply system could support with the given inflow. Thirdly, the impact of high-demand users such as elite housing and private baths, which require either significant volumes over long time periods or very large volumes over short periods of time could be investigated. Although there is a lack of evidence for locating these water-users within the city, some basic distribution data within the *Notitia Urbis* (see Matthews 2012) could act as a starting point. The results of such an investigation would enhance our understanding of the role of the cisterns and clarify what management operations might be required to support these larger water-users.
- The possible interconnection between the aqueducts is a major conclusion of this study. Adjusting the existing model to create an interconnected system would test its practicality. The intended purpose and use of the large open-air cisterns remains unresolved and studying the interconnection between the aqueducts would be a viable perspective from which to investigate the large open-air cisterns of Aspar and Aetius.
- From an archaeological perspective, considering the development of the water system through time could provide insight on how the water supply infrastructure influenced the development of the city, how lifestyles and associated water demand changed through time, and the extent to which the water supply system was resilient and able to be adapted during periods of crisis. However, this area of study is

challenging owing to the current lack of detail that would enable refinement of the agent-based model of the water supply system. Further archaeological work would be required – establishing likely changes in population, likely operational dates for cisterns, and more accurate location data for water-users – to enable a more detailed model and a consideration of the system through time.

- Another key finding in this study is that management decisions and actions were necessary for the successful performance of the system. This finding could be examined in more detail by considering methods of communication and performance monitoring and incorporating these into a range of decision-making models within the agent-based model of the system. Further investigation into this area might also provide a more conclusive answer on the question of merged or parallel arrangements on the Aqueduct of Valens.

## 9.5 A reflection on the process

At times, the radically different perspective proposed to move the understanding of the water supply forward also felt radically different to what was expected within a research setting. It was difficult to associate my own research actions with the generally positivist-slanted advice that was available. Yet my research actions corresponded with my experience as an engineer in industry. By the end of a design project I would develop an in-depth knowledge of the project in addition to the design solution and this was what I wanted to replicate in my research. Over time I found literature which supported this decision and confirmed it as a valid research method (as discussed in Section 4.2.3).

A view of myself as the engineer and the archaeological community as the client took hold. Reflecting on some of the examples of engineers working on archaeological subjects (discussed in Section 3.4), I always tried to focus on producing a “product” that was useful and intelligible and avoided applying engineering tools simply for the sake of producing data. This consideration of audience is a particularly important lesson for those working in multidisciplinary projects.

Overall this process has demonstrated the depth and richness of understanding that is possible when undertaking research into complex topics using non-traditional approaches.

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# Population density calculations

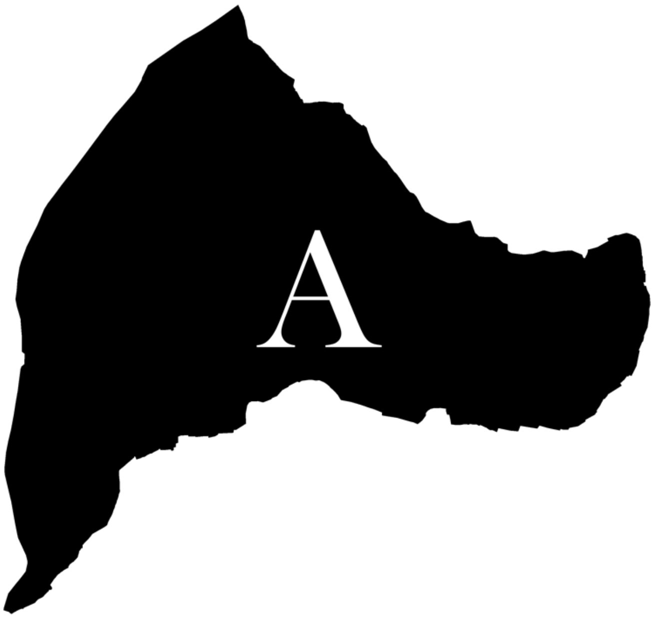
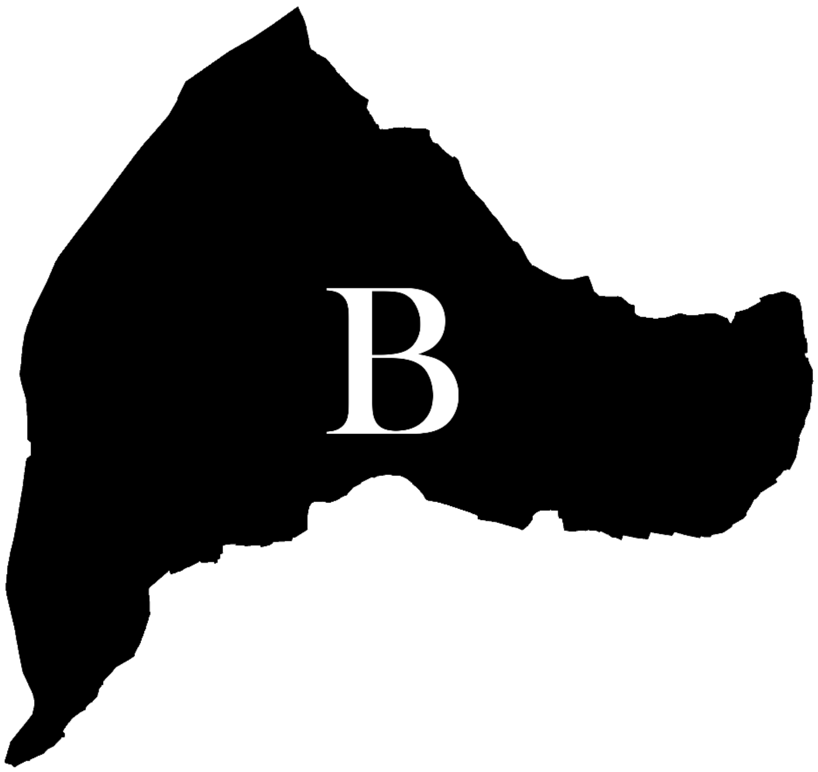


Table A.1: Population distribution calculations for 5th century

| Region | Area (ha) | Public bakeries | Private bakeries | Total bakeries (public weighted to equal 4 private) | Combined area (ha) | Combined population | Individual population | Population density (p/ha) |
|---|---|---|---|---|---|---|---|---|
| I | 45.1 | 4 | 15 | 35 | 83.8 | 28525 | 15352 | 340 |
| II | 38.7 | 0 | 4 | | | | 13173 | 340 |
| III | 27.4 | 0 | 9 | 9 | 27.4 | 7335 | 7335 | 268 |
| IV | 38.3 | 0 | 5 | 35 | 77.1 | 28525 | 14170 | 370 |
| V | 38.8 | 7 | 2 | | | | 14355 | 370 |
| VI | 35.8 | 1 | 17 | 33 | 93 | 26895 | 10353 | 289 |
| VII | 57.2 | 0 | 12 | | | | 16542 | 289 |
| VIII | 22.9 | 0 | 5 | 5 | 22.9 | 4075 | 4075 | 178 |
| IX | 59.7 | 4 | 15 | 36 | 59.7 | 29340 | 9540 | 160 |
| X | 112.9 | 2 | 16 | 31 | 302.6 | 25265 | 9426 | 83 |
| XI | 189.7 | 1 | 3 | | | | 15839 | 83 |
| XII | 123.9 | 0 | 5 | See IX | See IX | See IX | 19800 | 160 |
| IM | 571 | - | - | - | - | - | 28000 | 49 |

The total number of bakeries is 184 for a population of 150,000 (From Zone 1 and Zone 2 of Jacoby 1961), so each bakery equates to 815 people. Where populations have been combined, the individual region population is determined by a ratio of the regional area to the combined area.

# Comprehensive list of Byzantine cisterns



The Ref code is used on the accompanying map, the letter number combination identifies the grid square that the cistern occupies; the /number is the unique identifier for the cistern within that square. It was originally used by Müller-Wiener (1977) and the grid he used has been replicated in the accompanying map. The projection of Müller-Wiener's map is slightly different to the projections used within this project, so the grid is not perfectly aligned north-south/east-west.

The cistern name is given in English, Turkish or English and Turkish depending on the source.

The era uses Altuğ's (2013) data, so cisterns not included in his list are marked as "Not assessed".

Size details are in six categories as described in Section 6.2.2: Tiny <100 m$^3$; Small 100-999 m$^3$; Medium 1000 – 4999 m$^3$; Large 5000-99999 m$^3$; X-large >100000 m$^3$; Unknown.

The volume is given where known, or where a reasonable estimate can be made (where an estimate has been made this is given in the Notes column. Sources for volumes are varied – some information has been taken from Altuğ (2013) and other volumes have been provided by a database held by J Crow.

Source: A > Altuğ (2013); B > Both Altuğ (2013) and Crow *et al.* (2008); C > Crow *et al.* (2008)

Any relevant notes are included. Cisterns that were only included in Altuğ (2013) have been given a new MW Code, and, for reference, Altuğ's reference is included. Considerably more information is available for those cisterns included within Altuğ (2013). The references for each cistern within the literature have not been replicated here.

The cisterns included in this list are shown on Map B1 (A1 insert at rear).

| Ref | Name | Era | Size details | Volume (m$^3$) | Source | Notes |
|---|---|---|---|---|---|---|
| **A7/1** | Fatih Sitesi Sarnıcı | Late | Unknown | - | A | Given new MW code. Only a section of wall 1.13 m high and 3.35 m long remains. Altuğ ID 118 |
| **A10/1** | Mermer Kule Sarnıçları | Late | Small | 128 | A | Given new MW code. 4 adjacent tanks. 1.7 m deep 3Nr 5x4 m 1Nr 5x3 m. Altuğ ID 115 |
| **B6/1** | Mokios Reservoir<br>Mokios (Altımermer) Sarnıcı | Early | X-large | 374850 | B | Altuğ ID 123 |
| **B7/1** | Cistern South of Mokios Reservoir | Not assessed | Unknown | - | C | |
| **B8/1** | İnebey Sokağı Sarnıcı | Mid | Small | 258 | A | Given new MW code. Complex L shape surface area approximately 129 m² depth of 2 m is assumed. Altuğ ID 99 |
| **B8/2** | Koca Mustafa Paşa Camii Sarnıcı | Late | Small | 464 | A | Given new MW code. Altuğ ID 113 |
| **B8/3** | Ali Fakih Camii Avlusundaki Sarnıç | Unknown | Small | - | A | Given new MW code. No size information, not possible to enter. Altuğ ID 117 |
| **B9/1** | Cistern South of Stoudios basilica<br>Studios Sarnıcı | Early | Medium | 3165 | B | Altuğ ID 116 |
| **C1/1** | Cistern in Anemas Tower<br>Anemas Kulesi Sarnıc | Late | Small | 151 | B | Altuğ ID 158 |
| **C1/2** | Cistern near Ivaz Efendi Camii<br>Anemas Kulesi'nin Doğusundaki Sarnıç | Late | Small | 193 | B | The 3.5m depth is assumed to get the volume close to that stated in Crow's database with Altuğ's floor plan size. Altuğ ID 157 |

| Ref | Name | Era | Size details | Volume ($m^3$) | Source | Notes |
|---|---|---|---|---|---|---|
| **C1/3** | Cistern West of Atik Mustafa Pasa Camii | Not assessed | Unknown | - | C | |
| **C3/1** | Aetius reservoir<br>Aetius (Pulkheria?) Sarnıcı (Karagümrük Çukurbostan) | Early | X-large | 290360 | B | Altuğ ID 152 |
| **C3/2** | Cistern Ipek Bodrum<br>İpek Bodrumu | Mid | Medium | 2494 | B | Now destroyed. Altuğ ID 153 |
| **C3/3** | Cistern beneath Odalar Camii<br>Kemankeş Mustafa Paşa Camii'nin (Odalar Mescidi) A | Mid | Unknown | - | B | Approximately 3 x 9 m, depth unknown. Altuğ ID 154 |
| **C3/4** | Cistern East of Kefeli Mescidi<br>Kefeli Camii'nin Doğusundaki Sarnıç | Late | Small | 118 | B | Depth of 3.5 m is assumed. Altuğ ID 151 |
| **C3/5** | Cistern Lokunculer | Not assessed | Small | 158 | C | |
| **C3/6** | Cistern beneath Kariye Camii<br>Kariye Güney Şapeli (Pareklesion) Altındaki Sarnıç | Late | Small | 110 | B | Altuğ ID 155 |
| **C3/7** | Cistern South of Kariye Camii<br>Kariye Cami Sokak Sarnıcı | Mid | Tiny | 19.5 | B | 2 nr. vaults of the dimensions 3.1 x 2.1 x 1.5 m. Altuğ ID 156 |
| **C3/8** | Cistern near Edirne Kapi | Not assessed | Unknown | - | C | Previously listed as C3/9. Placed 75m from west corner of Aetius Reservoir, precise location unknown. |
| **C3/9** | Cistern in Kurt Aga Cesmesi Caddesi | Not assessed | Unknown | - | C | Previously listed as C3/10. Placed on Kurtaga Cesmesi Sok, precise location unknown. |
| **C4/1** | Cistern North of Nisanca Camii<br>Nişancı Mehmet Paşa Camii'nin Kuzeyindeki Sarnıç | Mid | Small | 370 | B | Altuğ ID 119 |
| **C4/2** | Cistern South-west of Fethiye Camii | Not assessed | Unknown | - | C | Question positioning in square C4- why not C3 or B3? Location unknown. |
| **C4/3** | Cistern North of Kara Gumruk Camii | Not assessed | Unknown | - | C | Previously C3/8. Placed between Kara Gumruk Camii and Aetius Reservoir, precise location unknown. |
| **C4/4** | Eski Ali Paşa Caddesi Sarnıcı | Unknown | Unknown | - | A | Given new MW code. No size information. Altuğ ID 122 |
| **C6/1** | Cistern under Fenari Isa Camii | Not assessed | Unknown | - | C | |
| **C7/1** | Cistern North of Hekimoglu Ali Pasa Camii<br>Hüseyin Kazım Sokak Sarnıcı | Mid | Small | 470 | B | 3.5 m depth is assumed. Altuğ ID 124 |
| **C8/1** | Marmaray, Yenikapı Sarnıcı | Early | Unknown | - | A | Given new MW code. No size info. Altuğ ID 38 |

| Ref | Name | Era | Size details | Volume (m³) | Source | Notes |
|---|---|---|---|---|---|---|
| **C8/2** | Sancaktar Tekkesi Sokak Sarnıçları | Mid | Small | 120 | A | Given new MW code. 4 5x3m cisterns side by side. 2m depth assumed. Altuğ ID 100 |
| **D3/1** | Cistern in Koroglu Sokak<br>Köroğlu Sokağı Sarnıcı | Mid | Small | 176 | B | Altuğ ID 129 |
| **D3/2** | Cistern East of Fethiye Camii<br>Fethiye Camii'nin Kuzeydoğusundaki Sarnıç | Mid | Small | 440 | B | 3 m depth assumed. Altuğ ID 128 |
| **D3/3** | Cistern West of Fethiye Camii<br>Fethiye İlköğretim Okulu Altındaki Sarnıç | Late | Medium | 1314 | B | Altuğ ID 127 |
| **D3/4** | Cistern at Sinan Pasa Mescidi<br>Sinan Paşa Mescidi'nin Doğusundaki Sarnıç | Late | Unknown | - | B | Approx. surface area 5.5 x 4.5 m. Altuğ ID 142 |
| **D3/5** | Cistern in Tabak Yunus Sokak<br>- | Not assessed | Unknown | - | C | Placed on Debbağ Yunus Sokak, precise location unknown. |
| **D3/6** | Cistern below Fethiye Camii<br>Fethiye Camii Altındaki Sarnıç | Mid | Small | 246 | B | Cross plus narthex shape. Some dimensions assumed including depth and smaller dimensions of cross. Altuğ ID 126 |
| **D3/7** | .-<br>Fethiye Caddesi Sarnıcı | Mid | Unknown | - | A | Given new MW code. Altuğ ID 125 |
| **D3/8** | .-<br>Yavuz Sultan Selim Camii Avlu Yanındaki I No.'lu S | Mid | Small | 675 | A | Given new MW code. Dimensions are approximate, scaled from drawing and aerial image. 3 m depth is assumed. Altuğ ID 131 |
| **D3/9** | .-<br>Yavuz Sultan Selim Camii Avlu Yanındaki II No'lu S | Mid | Small | 656 | A | Given new MW code. 3m depth assumed. Altuğ ID 132 |
| **D3/10** | .-<br>Ayakapı Şapeli Sarnıcı | Late | Unknown | - | A | Given new MW code. Complex shape- difficult to work out area & volume of cistern. No height info. Altuğ ID 141 |
| **D4/1** | Cistern East of Aspar reservoir<br>Sultan Sarnıç (Bonos Sarnıcı?) | Early | Medium | 2612 | B | Altuğ ID 121 |
| **D4/2** | Cistern on Muftu Hamami Sokak<br>Şeyh Murat Mescidi Yakınındaki Sarnıç | Mid | Small | 559 | B | 3 m depth is assumed. Around 19m remained at time of F&S inspection – unclear where length of 23m comes from. Altuğ ID 149 |
| **D4/3** | Cistern in Buyuk Otlukcu Yokusu<br>Büyük Otlukçu Yokuşu Sarnıcı | Mid | Medium | 4502 | B | Altuğ ID 120 |
| **D4/4** | Cistern North of Fatih Camii<br>Kirmasti Sarnıcı | Mid | Unknown | - | B | TWSoBC lists two cisterns 4a (Cistern below church north of Fatih Camii) and 4b (Cistern at south end of Halic Caddesi) 4b has not been included in this list/map the location should be opposite an old fire station (?). Altuğ ID 133 (associated with 4a) |

| Ref | Name | Era | Size details | Volume ($m^3$) | Source | Notes |
|---|---|---|---|---|---|---|
| **D4/5** | Cistern beneath Eski Imaret Camii<br>Eski İmaret Camii Altındaki Sarnıç | Mid | Small | 210 | B | Complex shape. 2 m depth is assumed from F&S sketch. Altuğ ID 139 |
| **D4/6** | Aspar Reservoir<br>Aspar Sarnıcı (Çarşamba Çukurbostanı) | Early | X-Large | 249523 | B | Altuğ ID 130 |
| **D4/7** | Cistern on Fodlaci Sokak<br>- | Not assessed | Unknown | - | C | |
| **D5/1** | Cistern West of Zeyrek Camii<br>İbadethane Sokağı I No.'lu Sarnıç | Mid | Medium | 1277 | B | 4 m depth is assumed as structure is filled with earth. Altuğ ID 145 |
| **D5/2** | Cistern on Haci Hasan Sokak<br>Hacı Hasan Sokak Sarnıcı | Early | Unknown | - | B | Remaining bit of wall is 10m long. No other dimensions. Altuğ ID 148 |
| **D5/3** | Cistern x2 north of Seyh Suleyman Mescidi<br>Şeyh Süleyman Mescidi'nin Kuzeyindeki Sarnıç | Mid | Small | 455 | B | 3m depth assumed. Gallery supplying water on the south wall and water channels on the west wall. Altuğ ID 144 |
| **D5/4** | Cistern at Sarachane<br>- | Early | Large | 80000 | C | Conservative volume assumption. Forchheimer & Strzygowski (1893) report sections of wall of 154 m and 90 m in length assume fill depth ~6 m. |
| **D5/5** | Cistern on North flank of Fatih Camii<br>Fatih Camii Avlusundaki Sarnıç | Early | Medium | 3359 | B | This is a minimum size as cistern is partially in ruins and filled with earth. Mention of water channel in corner. Altuğ ID 137 |
| **D5/6** | Cistern at Cukur Hamami<br>- | Not assessed | Unknown | - | C | |
| **D5/7** | Cistern South-east of Fatih Camii<br>- | Not assessed | Unknown | - | C | |
| **D5/8** | F&S z | F&S z | | | | Excluded from map as location uncertain. Forchheimer & Strzygowski (1893) |
| **D5/9** | Cistern in Mihcilar Caddesi<br>At Pazarı Sarnıcı | Mid | Medium | 1616 | B | 3 m depth is assumed. Volume is for central section only. Altuğ ID 136 |
| **D5/10** | .-<br>Tezgahçılar Kubbesi | Early | Unknown | - | A | Given new MW code. This is not a cistern - a flow division point (in Ottoman times) Altuğ ID 143 |
| **D6/1** | Cistern west of Marcian's column<br>Kambur Mustafa Paşa (Yayla) Camii Altındaki Sarnıç | Early | Medium | 1497 | B | Altuğ ID 134 |

| Ref | Name | Era | Size details | Volume ($m^3$) | Source | Notes |
|---|---|---|---|---|---|---|
| **D6/2** | Cistern near Orta Cesme<br>Ahmediye Camii Altındaki Sarnıç (Ortaçeşme-Etmeyda | Early | Small | 885 | B | Potentially interesting detail of shaft at entrance in F&S. Altuğ ID 135 |
| **D6/3** | Cistern West of Marcian's column<br>Sofular Caddesi'ndeki Sarnıç | Mid | Small | 765 | B | Altuğ ID 110 |
| **D6/4** | Cistern South of Marcian's column<br>- | Unknown | Unknown | - | C | Altuğ says possibly not a cistern. |
| **D6/5** | Cistern at Alaettin Mescidi<br>Bıçakçı Alaeddin Mescidi Sarnıcı | Early | Unknown | - | B | Water still flows. Altuğ ID 111 |
| **D6/6** | Cistern in Molla Husrev Sokak | Not assessed | Unknown | - | C | Placed on Molla Husrev Sokak, precise location unknown. |
| **D6/7** | Polyeuktos Kilisesi Sarnıcı | Late | Unknown | - | A | Given new MW code. No size information, supply from the South? Altuğ ID 98 |
| **D6/8** | Defter Emini Sokak Sarnıcı | Unknown | Tiny | 64 | A | Given new MW code. Rock carved, hole in roof for access to water? Altuğ ID 104 |
| **D7/1** | Cistern remains at Haseki Caddesi | Not assessed | Unknown | - | C | |
| **D7/2** | Cistern in rotunda beside Bodrum Camii (Myrelaion)/Myrelaion Sarnıcı | Mid | Small | 785 | B | Volume based on an internal diameter of 20m and an assumed depth of 2.5m. Altuğ ID 94 |
| **D7/3** | Murat Paşa Camii Yanındaki Sarnıç | Early | Small | 288 | A | Given new MW code. Length is equivalent for each room, 3 m depth is assumed. Altuğ ID 95 |
| **E4/1** | Cistern by Sea Walls at Cibali Kapi/Seferikoz Sarnıcı | Mid | Medium | 1747 | B | Altuğ ID 109 |
| **E4/2** | Cistern below Kadir Has Universitesi/Üsküplü Caddesi Sarnıcı | Unknown | Tiny | 50 | B | Volume reduced to account for barrel vault formation. Small room not considered. Altuğ ID 108 |
| **E4/3** | Bıçakçı Çeşme Sokak Sarnıç ve Ayazması | Mid | Unknown | - | A | Given new MW code. Approx dimensions 20 x 14 m. Altuğ ID 106 |
| **E4/4** | Tepedelen Çeşmesi Sokak Sarnıcı | Early | Unknown | - | A | Given new MW code. Sizes are minimum (8.5 x 6.2 m, depth unknown), probably bigger. Altuğ ID 107 |
| **E4/5** | Haydar Hamamı Sokak Sarnıcı | Unknown | Tiny | - | A | Given new MW code. L shaped Altuğ ID 138 |
| **E4/6** | Haydar Bostanı Sokağı Sarnıcı | Unknown | Unknown | - | A | Given new MW code. Altuğ ID 140 |
| **E4/7** | Unkapanı Sarnıcı | Mid | Unknown | - | A | Given new MW code. Altuğ ID 150 |
| **E5/1** | Cistern West of Zeyrek Camii | Not assessed | Unknown | - | C | |

| Ref | Name | Era | Size details | Volume ($m^3$) | Source | Notes |
|---|---|---|---|---|---|---|
| **E5/2** | Cistern Unkapani on Ataturk Bulvari/Zeyrek (Pantokrator) Sarnıcı | Mid | Large | 5940 | B | Visited Nov 2014. Altuğ ID 105 |
| **E5/3** | Cistern South-west of Zeyrek Camii/İbadethane Sokağı III No.'lu Sarnıç | Mid | Unknown | - | B | Altuğ ID 147 |
| **E5/4** | Cistern West of Zeyrek Camii/İbadethane Sokağı II No.'lu Sarnıç | Mid | Unknown | - | B | Altuğ ID 146 |
| **E5/5** | Cistern at Yogurtcu Oglu Medrese | Not assessed | Unknown | - | C | |
| **E5/6** | Cistern South of Zeyrek Camii | Not assessed | Unknown | - | C | |
| **E5/7** | Cistern in Sabunhanesi Sokak | Not assessed | Unknown | - | C | |
| **E5/8** | F&S d | | | | | Excluded from list, location uncertain. |
| **E5/9** | F&S e | | | | | Excluded from list, location uncertain. |
| **E5/10** | Cistern North-east of Zeyrek Camii | Not assessed | Unknown | - | C | |
| **E5/11** | F&S q | | | | | Excluded from list, location uncertain. |
| **E5/12** | F&S c | | | | | Excluded from list, location uncertain. |
| **E5/13** | Cistern North of Hacikadin hamam/İMÇ Sarnıcı | Late | Small | 172 | B | Altuğ ID 72 |
| **E5/14** | Cistern South of Sepsefa Hatun Camii | Not assessed | Unknown | - | C | Placed south of the Sepsefa Hatun Camii, precise location unknown. |
| **E5/15** | Cistern South of Kilise Camii | Not assessed | Unknown | - | C | |
| **E5/16** | Open cemetery near Suleymaniye/Müşkile Sokak Sarnıcı | Mid | Small | 159 | B | Double room cistern length breadth for larger room, volume is combined. Altuğ ID 102 |
| **E5/17** | Fetva Yokuşu Sarnıcı | Unknown | Unknown | - | A | Given new MW code. Altuğ ID 70 |
| **E5/18** | Hoca Hamza Mescidi Altındaki Sarnıç | Mid | Unknown | - | A | Given new MW code. Altuğ ID 71 |
| **E5/19** | Vefa Kilise Camii'nin Batısındaki Sarnıç | Mid | Unknown | - | A | Given new MW code. Altuğ ID 73 |
| **E5/20** | İmaret Sabunhanesi Sokağı Sarnıcı | Unknown | Small | 132 | A | Given new MW code. Complex shape with multiple barrel vaults. Altuğ ID 74 |

| Ref | Name | Era | Size details | Volume ($m^3$) | Source | Notes |
|---|---|---|---|---|---|---|
| **E5/21** | Vefa Meydanı Sarnıcı | Mid | Unknown | - | A | Given new MW code. No size info. Altuğ ID 101 |
| **E6/1** | Cistern North of Beyazit medrese/Beyazıt Sarnıcı II | Early | Small | 286 | B | Concluded that E6/7 (previously included in the TWSoBC concordance) is the same as E6/1 (Cross check with Kerim's catalogue). Altuğ ID 77 |
| **E6/2** | Cistern on Vezneciler Caddesi/Beyazıt Sarnıcı I | Late | Medium | 2400 | B | Only part of the cistern remains length (40 m) and depth (3 m) are assumed. Altuğ ID 76 |
| **E6/3** | Cistern in Aga Yokusu Sokak/Ağa Yokuşu Sarnıcı | Unknown | Small | 115 | B | Altuğ ID 93 |
| **E6/4** | Cistern in Muh. Emin Pasa Sokak | Not assessed | Unknown | - | C | |
| **E6/5** | Cistern at East end of Bozdoğan Kemeri | Not assessed | Unknown | - | C | |
| **E6/6** | Cistern West of Beyazit Camii (northern cistern) | Not assessed | Unknown | - | C | |
| **E6/7** | Removed - same as E6/1 | | | | | |
| **E6/8** | Cistern north of Beyazit hamam | Not assessed | Unknown | - | C | |
| **E6/9** | F&S b | | | | | Excluded from list, location uncertain. |
| **E6/10** | Cistern on Universite Caddesi/Beyazıt Sarnıcı III | Unknown | Medium | 2241 | B | Altuğ ID 78 |
| **E6/11** | Cistern in Cadircilar Caddesi | Not assessed | Unknown | - | C | |
| **E6/12** | Cistern North of Laleli Camii | Not assessed | Unknown | - | C | Placed on Cukur Cesme Sokak, precise location unknown. |
| **E6/13** | 5Nr. Cisterns at University excavations west of Beyazit/Beyazıt B Kilisesi'nin Kuzeyindeki Sarnıç | Unknown | Unknown | - | B | Cistern with Kerim ID 79 is one of the 5 Nr cisterns. |
| **E6/14** | Cistern in Children's Library/Süleymaniye Sıbyan Mektebi Avlusundaki Sarnıç | Mid | Unknown | - | B | Inflow/outflow channels present. Altuğ ID 69 |
| **E6/15** | Mercan Sarnıcı | Early | Small | 352 | A | Given new MW code. cistern continues under street full dimensions unknown, volume given is probably an underestimate. Altuğ ID 56 |
| **E6/16** | Kirazlı Mescid Sarnıcı | Early | Small | 105 | A | Given new MW code. Two roomed cistern. dimensions estimated for the larger room. Altuğ ID 75 |
| **E6/17** | Sarnıçlı Han Sarnıcı | Mid | Unknown | - | A | Given new MW code. Two storey cistern (accessible to the public?) no size info. Altuğ ID 82 |
| **E6/18** | Adem İş Hanı Altındaki Sarnıç | Early | Tiny | 61 | A | Given new MW code. dimensions are approximate. Altuğ ID 83 |
| **E6/19** | Harikzadeler Sokak Sarnıcı | Unknown | Tiny | 68 | A | Given new MW code. Altuğ ID 84 |
| **E6/20** | Delikanlı Sokak Sarnıcı | Early | Tiny | - | A | Given new MW code. Altuğ ID 85 |

| Ref | Name | Era | Size details | Volume ($m^3$) | Source | Notes |
|---|---|---|---|---|---|---|
| **E6/21** | Onaltı Mart Şehitleri Caddesi Sarnıcı | Unknown | Tiny | - | A | Given new MW code. Altuğ ID 86 |
| **E6/22** | Büyük Reşit Paşa Caddesi Sarnıcı | Early | Unknown | - | A | Given new MW code. Above street level to the South – Vezneciler excavation. Altuğ ID 96 |
| **E6/23** | Vidinli Tevfik Paşa Caddesi Sarnıcı | Mid | Small | 180 | A | Given new MW code. All dimensions assumed only part of the cistern remains. Altuğ ID 97 |
| **E7/1** | Cistern on Forum Tauri | Not assessed | Unknown | - | C | |
| **E7/2** | | | | | | Excluded from list – suspected to be the same as Altuğ ID 88 (E7/8) |
| **E7/3** | Cistern in Bodrumhan in Grand Bazaar | Not assessed | Unknown | - | C | |
| **E7/4** | Cistern West of Beyazit Camii (southern cistern) | Not assessed | Unknown | - | C | |
| **E7/5** | Cistern below Antik Hotel, Beyazit/Antik Otel Sarnıcı | Early | Medium | 1500 | B | Dimensions are uncertain, particularly depth, 5m assumed from max wall height of 6.5m. Altuğ ID 89 |
| **E7/6** | Ordu Caddesi Sarnıcı | Mid | Tiny | 85 | A | Given new MW code. Consists of two cisterns of similar size connected by channel. Volume is for both. Altuğ ID 80 |
| **E7/7** | Akgün Otel Sarnıcı | Early | Small | 607 | A | Given new MW code. Altuğ ID 81 |
| **E7/8** | Star İş Merkezi Altındaki Sarnıç | Early | Small | 912 | A | Given new MW code. 4 interconnected barrel vault cisterns possibly associated with a bath to the North. volume is for all 4 cisterns. Altuğ ID 88 |
| **E7/9** | Türk Telekom Kumkapı Santrali Sarnıcı | Early | Unknown | - | A | Given new MW code. No size info available. Altuğ ID 90 |
| **E7/10** | Turkuaz İş Merkezi Altındaki Sarnıç | Early | Tiny | 69 | A | Given new MW code. minimum volume, height based on remaining wall. Altuğ ID 91 |
| **E7/11** | Mesihpaşa Caddesi Sarnıcı | Unknown | Unknown | - | A | Given new MW code. No size information. Altuğ ID 92 |
| **E7/12** | Asya Sokak Sarnıcı | Unknown | Tiny | 2 | A | Given new MW code. Altuğ ID 103 |
| **E7/13** | Asker Sokak Sarnıcı | Unknown | Unknown | - | A | Given new MW code. Altuğ ID 114 |
| **E8/1** | Cisterns x2 in Arapzade Sok., Kumkapi/Üstad Sokağı Sarnıcı | Unknown | Tiny | 72 | B | Volume is for the two cisterns, 3m depth is assumed. Altuğ ID 51 |
| **F3/1** | #N/A | #N/A | #N/A | | #N/A | Located on the Galata peninsula, noted in TWSoBC but not included in this study |
| **F4/1** | #N/A | #N/A | #N/A | | #N/A | Located on the Galata peninsula, noted in TWSoBC but not included in this study |
| **F6/1** | Cistern beneath Istanbul Erkek Lisesi/İstanbul Lisesi Altındaki Sarnıç | Early | Small | 360 | B | 3m depth is assumed. Altuğ ID 62 |
| **F6/2** | Cistern on West side of Mangene Cik/Mengene Sokağı Sarnıcı | Early | Small | 213 | B | Altuğ ID 67 |

| Ref | Name | Era | Size details | Volume (m$^3$) | Source | Notes |
|---|---|---|---|---|---|---|
| **F6/3** | Cistern Baltaci Hani/Daye Kadın Sokağı Sarnıcı | Unknown | Small | 903 | B | Altuğ ID 66 |
| **F6/4** | Cistern in American Bible House/Bible House Sarnıcı | Early | Small | 179 | B | Altuğ ID 68 |
| **F6/5** | Cistern substructures on Cemal Nadir Sokak/Acımusluk Sokağı Sarnıcı | Mid | Small | 845 | B | Complicated shape with multiple rooms. 2.5m effective depth assumed. Altuğ ID 64 |
| **F6/6** | Cistern East of Hoca Kasim Kopru Caddesi/Besler Han Sarnıcı | Unknown | Small | 276 | B | Altuğ ID 63 |
| **F6/7** | Cistern North-west ofIstanbul Erkek Lisesi/İstanbul Lisesi Yurt Binası Sarnıcı | Early | Unknown | - | B | No size info, sketch with dimensions unreadable. Altuğ ID 61 |
| **F6/8** | 2No. cisterns in Ferdi Gorcay Sokak | Not assessed | Unknown | - | C | Placed on Celal Ferdi Gorcay Sokak, precise location unknown. |
| **F6/9** | Cistern at Çatalçeşme Sokak | Not assessed | Unknown | - | C | |
| **F6/10** | Cistern North of American Bible House | Not assessed | Unknown | - | C | |
| **F6/11** | Cistern built over buildings at Vilayet | Not assessed | Unknown | - | C | |
| **F6/12** | Cistern in printing house on Mengene Sokak | Not assessed | Unknown | - | C | |
| **F6/13** | 3 no cisterns in Tarakçı Cafer Sok. | | | | | Excluded from list – probable overlap with F6/15. |
| **F6/14** | Cistern below Nurosmaniye Camii | Not assessed | Unknown | - | C | |
| **F6/15** | Tarakçı Cafer Sokak Sarnıcı | Unknown | Small | 129 | A | Given new MW code. Altuğ ID 65 |
| **F6/16** | Nuruosmaniye Caddesi'ndeki Küçük Sarnıç | Early | Unknown | - | A | Given new MW code. No size info other than depth may have been 4.5-5.5 m. Altuğ ID 57 |
| **F7/1** | Cistern on Divani Ali Sokak next to Kara Mustafa Pasa Medrese/Çiftesaraylar Sarnıcı | Early | Small | 360 | B | 3 m depth assumed from total depth to sail vault of 3.5 m. Dimensions of part of cistern? Altuğ ID 112 |
| **F7/2** | Cistern on Seref Efendi Sokak/Nuruosmaniye Sarnıcı | Early | Small | 774 | B | Altuğ ID 60 |
| **F7/3** | Cistern beneath Eminonu Belediyesi/Şerefiye Sarnıcı | Early | Large | 7254 | B | Altuğ ID 55 |

| Ref | Name | Era | Size details | Volume ($m^3$) | Source | Notes |
|---|---|---|---|---|---|---|
| **F7/4** | Cistern North of Dizdariye Cesmesi Sokak/Dizdariye Sarnıcı | Early | Tiny | 78 | B | Altuğ ID 47 |
| **F7/5** | Binbirdirek cistern/Binbirdirek (Philoksenos?) Sarnıcı | Early | Large | 42954 | B | Altuğ ID 53 |
| **F7/6** | Cistern West of Firuz Aga Camii/Lausos Sarayı Rotundası Kuzeyindeki Sarnıç | Unknown | Unknown | - | B | Altuğ ID 40 |
| **F7/7** | Cistern on Bab-i-Ali Caddesi/Cağaloğlu Sarnıcı | Early | Unknown | 35000 | B | Altuğ ID 59. Conservative volume estimate. Depth at least 14 m, length of wall remaining 90 m. |
| **F7/8** | Cistern in rotunda North of hexagon of Antiochus | Not assessed | Unknown | - | C | |
| **F7/9** | Cistern in great hall North of hexagon of Antiochus/Lausos Sarayı Büyük Salonu "Sarnıcı" | Early | Medium | 2604 | B | Size is rough estimate. Altuğ ID 39 |
| **F7/10** | Muhterem Efendi Sokak Sarnıcı | Early | Small | 480 | A | Given new MW code. 4m depth is assumed. Altuğ ID 28 |
| **F7/11** | Bestekar Osman Sokak Sarnıcı | Unknown | Tiny | 35 | A | Given new MW code. Altuğ ID 29 |
| **F7/12** | Salkım Söğüt Sokak Sarnıcı | Early | Unknown | - | A | Given new MW code. Altuğ ID 31 |
| **F7/13** | Katip Sinan Cami Sokak Sarnıcı | Early | Unknown | - | A | Given new MW code. Altuğ ID 46 |
| **F7/14** | Tahsin Bey Sokağı Sarnıcı | Early | Small | 117 | A | Given new MW code. 2m depth assumed. Altuğ ID 48 |
| **F7/15** | Doğramacı Emin Çıkmazı Sarnıcı | Early | Unknown | - | A | Given new MW code. Altuğ ID 49 |
| **F7/16** | Araç İş Hanı Sarnıcı | Unknown | Unknown | - | A | Given new MW code. depth is max height of vault. Altuğ ID 50 |
| **F7/17** | Gedikpaşa Caddesi Sarnıcı | Mid | Small | 246 | A | Given new MW code. Altuğ ID 52 |
| **F7/18** | Işık Sokak Sarnıcı | Unknown | Unknown | - | A | Given new MW code. Altuğ ID 54 |
| **F7/19** | Cağaloğlu Anadolu Lisesi Bahçesindeki Sarnıç | Unknown | Unknown | - | A | Given new MW code. Altuğ ID 58 |
| **F8/1** | Cistern on Nakilbent Sokak/Nakilbent Sokağı Sarnıcı | Early | Small | 940 | B | 3m depth is assumed. Altuğ ID 37 |
| **F8/2** | Cistern in Oğul Sokak | Not assessed | Unknown | - | C | |
| **F8/3** | Cistern under staircase in Boukoleon Palace/Bukoleon Sarayı Merdiveni Altındaki Sarnıç | Mid | Unknown | - | B | Altuğ ID 35 |
| **F8/4** | Cistern beneath floor of Great Palace peristyle | Not assessed | Unknown | - | C | |
| **F8/5** | Cistern in Sphendone of Hippodrome/Hippodrom Sarnıcı | Early | Medium | 3298 | B | Complex shape, changing with depth. 4m depth is assumed, deeper water is possible. Altuğ ID 45 |

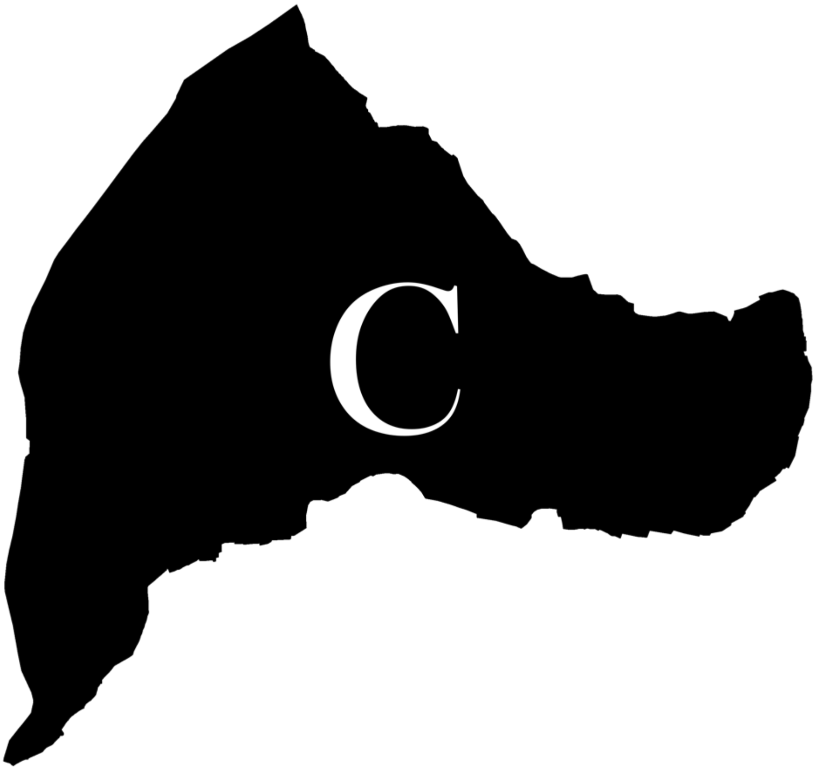
| Ref | Name | Era | Size details | Volume (m³) | Source | Notes |
|---|---|---|---|---|---|---|
| **F8/6** | Cistern in Eresin Crown Hotel foyer/ Eresin Otel Sarnıcı | Early | Unknown | - | B | Altuğ ID 41 |
| **F8/7** | Cistern on South flank of Apsed hall/Torun Sokak Sarnıcı | Unknown | Unknown | - | B | Altuğ ID 36 |
| **F8/8** | Çayıroğlu Sokak Sarnıcı | Early | Unknown | - | A | Given new MW code. Altuğ ID 42 |
| **F8/9** | Kapı Ağası Mahmut Ağa Camii Altındaki Sarnıç | Early | Unknown | - | A | Given new MW code. Altuğ ID 43 |
| **F8/10** | Küçük Ayasofya Ayazması Sarnıcı | Early | Unknown | - | A | Given new MW code. Altuğ ID 44 |
| **F8/11** | Sokullu Oteli Sarnıcı | Early | Unknown | - | A | Given new MW code. Altuğ ID 87 |
| **G6/1** | Cistern in Gulhane park (former aquarium)/Gülhane Parkı Sarnıcı | Early | Medium | 1504 | B | Altuğ ID 1 |
| **G6/2** | Cistern beneath Topkapi Sarayi | Not assessed | Unknown | - | C | |
| **G6/3** | Cistern in Archaeological Museum court/İstanbul Arkeoloji Müzeleri Avlusundaki Sarnıç | Early | Large | 5625 | B | Altuğ ID 24 |
| **G6/4** | Cistern below North wing of Archaeological Museum | Not assessed | Unknown | - | C | |
| **G6/5** | Cistern East of Archaeological Museum/İstanbul Arkeoloji Müzeleri Ek Binası Büyük Sarnıç | Early | Unknown | - | B | 45 x 25 m, depth uncertain. Altuğ ID 12 |
| **G6/6** | Cistern West of Mangana Palace/Hagios Georgios Manastırı Avlusundaki Sarnıç | Mid | Medium | 1518 | B | Altuğ ID 6 |
| **G6/7** | Cistern North of Haghia Eirene/İstanbul Arkeoloji Müzeleri Ek Bina Sarnıçları | Unknown | Unknown | - | B | No size info. Altuğ ID 11 |
| **G6/8** | Cistern in Topkapi second court/Babüssaade'ye Giden Yol Üzerindeki Sarnıç | Early | Unknown | - | B | Altuğ ID 18 |
| **G6/9** | Cistern North of Haghia Eirene/Eski Darphane'nin Köşesindeki Sarnıç | Early | Large | 5250 | B | 5m depth is assumed. Altuğ ID 20 |
| **G6/10** | Cistern in Topkapi second court/Topkapı Sarayı, Kubbealtı Önündeki Sarnıç | Early | Unknown | - | B | Query dimensions given (claim 20 x 15 m). Altuğ ID 13 |

| Ref | Name | Era | Size details | Volume ($m^3$) | Source | Notes |
|---|---|---|---|---|---|---|
| **G6/11** | Cistern in Topkapi third court/Gözdeler Taşlığı Altındaki Sarnıç | Early | Small | 570 | B | Altuğ ID 16 |
| **G6/12** | Cistern in Topkapi third court/Hırka-i Saadet Dairesi Önündeki Sarnıç | Early | Small | 499 | B | Altuğ ID 17 |
| **G6/13** | Cistern below buildings near Goth's column | Not assessed | Unknown | - | C | |
| **G6/14** | Cistern beside Alay Kosku | Not assessed | Unknown | - | C | |
| **G6/15** | Cistern in Topkapi second court/Saray Mutfaklarına Giden Yol Üzerindeki Sarnıç | Unknown | Tiny | 11 | B | Altuğ ID 14 |
| **G6/16** | Cistern below St George in the Mangana/Hagios Georgios Manastırı Alt Yapısı | Mid | Large | 5852 | B | Unclear if these dimensions refer to part or all of the cistern. 10 m depth is suspect. Altuğ ID 4 |
| **G6/17** | Cistern East of St George in the Mangana | Not assessed | Unknown | - | C | |
| **G6/18** | Nöbethane Caddesi Sarnıcı | Early | Tiny | 40 | A | Given new MW code. 2m depth is assumed. Altuğ ID 26 |
| **G7/1** | Cistern at Arslanhane Kapisi/Eski Depolar Komutanlığı Altındaki Sarnıç | Early | Small | 794 | B | Altuğ ID 7 |
| **G7/2** | Cebehane cistern/Benzinlik, Barutluk Sarnıcı | Early | Medium | 1007 | B | Altuğ ID 10 |
| **G7/3** | Cistern beneath Gulhane Hospital/Eski Gülhane Askeri Hastanesi Altındaki Sarnıç | Early | Medium | 2445 | B | Altuğ ID 8 |
| **G7/4** | Cistern beneath Gulhane Hospital | Not assessed | Unknown | - | C | |
| **G7/5** | Cistern South of Haghia Eirene/Aya İrini Güneydoğusundaki "L" Şeklindeki Sarnıç | Early | Large | 5584 | B | L-shaped. Altuğ ID 23 |
| **G7/6** | Cistern in first court of Topkapi Sarayi/Topkapı Sarayı Bodrum II Sarnıcı | Mid | Small | 284 | B | Altuğ ID 3 |
| **G7/7** | Cistern in first court of Topkapi Sarayi/Topkapı Sarayı Bodrum I Sarnıcı | Mid | Small | 366 | B | Altuğ ID 2 |

| Ref | Name | Era | Size details | Volume ($m^3$) | Source | Notes |
|---|---|---|---|---|---|---|
| **G7/8** | Cistern North of Gulhane Hospital/Cephanelik Sarnıcı | Unknown | Tiny | 64 | B | 2 m depth is assumed. Altuğ ID 15 |
| **G7/9** | Basilica Cistern/Yerebatan (Bazilika) Sarnıcı | Early | Large | 80233 | B | Altuğ ID 27 |
| **G7/10** | Cistern North-west of Gulhane Hospital/Eski Gülhane Askeri Hastanesi Avlusundaki Sarnıç | Early | Medium | 1512 | B | Altuğ ID 9 |
| **G7/11** | Cistern South-East of Haghia Sophia | Not assessed | Unknown | - | C | |
| **G7/12** | Cistern South of Haghia Eirene/Aya İrini Bitişiğindeki 10 No.'lu Sarnıç | Early | Unknown | - | B | Altuğ ID 21 |
| **G7/13** | Cistern East of Haghia Eirene/Kimyahane Sarnıcı | Mid | Medium | 2288 | B | Altuğ ID 19 |
| **G7/14** | Cistern under Palace of Justice/Ayasofya'nın Güneydoğusundaki Sarnıç | Early | Unknown | - | B | No indication of size in description. Altuğ ID 33 |
| **G7/15** | Cistern on North side of Sogukcesme Sokagi (restaurant)/Soğukçeşme Sokağı Sarnıcı | Mid | Medium | 1584 | B | Altuğ ID 25 |
| **G7/16** | Cistern on South side of Sogukcesme Sokagi (hotel bar)/Turing Konuk Evi Sarnıcı | Early | Small | 125 | B | 2.5 m depth is assumed. Altuğ ID 30 |
| **G7/17** | Cisterns below Haghia Sophia/Ayasofya İç Nartheksin Altındaki Mekan | Early | Small | 231 | B | Altuğ ID 32 |
| **G7/18** | Cistern below Mangana Palace/Manganlar Sarayı Alt Yapısı | Mid | Large | 9526 | B | Altuğ ID 5 |
| **G7/19** | Cistern in front of Gulhane military school | Not assessed | Unknown | - | C | Placed based on location of military school on Stolpe map, precise location unknown. |
| **G7/20** | Removed - same as F7/10 | | | | | |
| **G7/21** | Cistern South of Haghia Eirene/Aya İrini Kazı Alanındaki 11 No.'lu Sarnıç | Early | Medium | 1094 | B | 5m depth assumed. Altuğ ID 22 |
| **G7/22** | Saraçhane Çıkmazı Sarnıcı | Early | Unknown | - | A | Given new MW code. No indication of size. Altuğ ID 34 |

| Ref | Name | Era | Size details | Volume ($m^3$) | Source | Notes |
|---|---|---|---|---|---|---|
| **G8/1** | Cistern East of Great Palace Apsed Hall | Early | Unknown | - | C | |
| **G8/2** | Cistern between the 'House of Justinian' and Ahir Kapi | Not assessed | Unknown | - | C | Placed close to Ahir Kapi, precise location unknown. |

# Background to the water wealth map



## The water wealth map

The idea behind the water wealth map is to capture the complex interaction of population density, cistern distribution and volume of storage within those cisterns. In combination these offer a view of access to water.

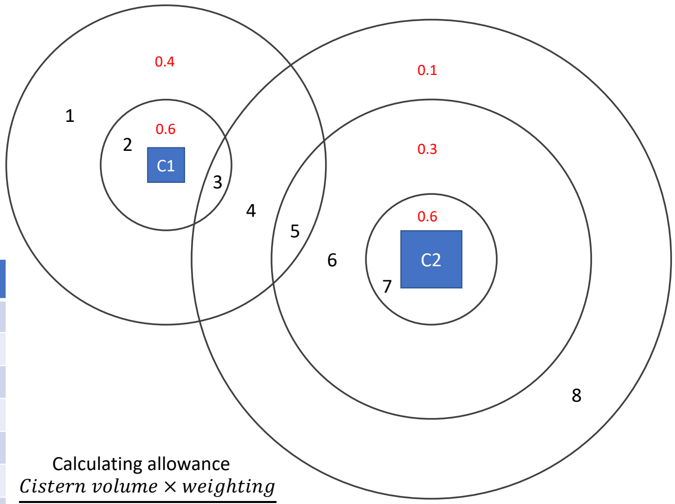
## Cistern sphere of influence

Each cistern was assumed to be accessible to the population in close proximity to it, with the larger cisterns being accessible to people for a greater distance, to reflect that the larger cisterns maybe better known and potentially more reliable so could potentially draw in more people. Water is heavy, so people are more likely to go the cistern(s) closest to them to minimise the distance that water has to be carried. To reflect this, a set of distance bands with a weighting that decreases with distance from the cistern was established, shown in T.[86] The basic calculation of water wealth is illustrated in 341. Replicating this for Constantinople is more difficult because the multiple rings around the 87 cisterns included in the analyses create a lot of overlap.

C1 volume = 2500 m$^3$

C2 volume = 7000 m$^3$

| | Population | C1 allowance | C2 allowance | Total (m$^3$/person) |
|---|---|---|---|---|
| 1 | 3500 | 0.16 | - | 0.16 |
| 2 | 1800 | 0.70 | - | 0.70 |
| 3 | 350 | 0.70 | 0.08 | 0.78 |
| 4 | 2000 | 0.16 | 0.08 | 0.24 |
| 5 | 700 | 0.16 | 0.45 | 0.61 |
| 6 | 4000 | - | 0.45 | 0.45 |
| 7 | 1500 | - | 2.8 | 2.8 |
| 8 | 6000 | - | 0.08 | 0.08 |



Calculating allowance

$$\frac{Cistern\ volume \times weighting}{Population\ of\ band}$$

Figure C.1: Example of water wealth calculation

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[86] On reflection, further work is required testing and defining appropriate distance bands and weightings.

Table C.1: Cistern distance bands and weighting

| | 250 | 500 | 750 | 1000 | 1500 |
|---|---|---|---|---|---|
| Tiny | - | - | - | - | - |
| Small | 0.6 | 0.4 | - | - | - |
| Medium | 0.6 | 0.3 | 0.1 | - | - |
| Large | 0.5 | 0.25 | 0.2 | 0.05 | - |
| Extra-Large | 0.5 | 0.2 | 0.15 | 0.1 | 0.05 |

To create the map in ArcGIS:

1. Create multiple ring buffers according to cistern size (refer Table C.1) and add the weighting figure as an attribute.
2. Add the population data to rings: Union of multiple rings with regions (use pop density x area). This create multiple polygons from the many overlaps.
3. Create a point inside each step 2 polygon (Feature to Point tool)
4. Perform a one-to-many spatial join, joining the attributes of the original polygons (step 1) with the points created in step 3. Make sure to transfer the attributes: population, buffer distance, buffer weighting and volume of cistern.
5. Summarise the attributes connected to each point and join back to the step 2 polygons.

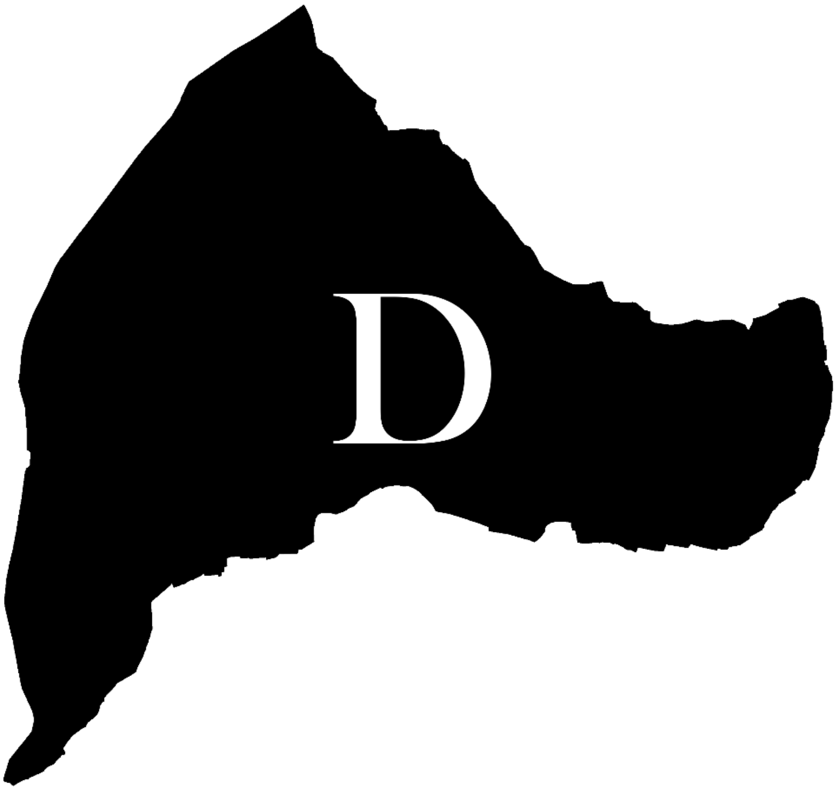
This is the "spaghetti and meatballs" overlay technique detailed on the ESRI (ArcGIS) blog here: https://blogs.esri.com/esri/arcgis/2012/11/26/spaghetti_meatballs_one_to_many/

# Published Papers

This appendix contains pre-prints of the following papers:

Ward, K., Crow, J., and Crapper, M. 2017. Water-supply infrastructure of Byzantine Constantinople. *Journal of Roman Archaeology 30*, 175–195. https://doi.org/10.1017/S1047759400074079

Ward, K., Crapper, M., Altuğ, K., & Crow, J. (2017). The Byzantine cisterns of Constantinople. *Water Science and Technology: Water Supply*, 6, 1499-1506. https://doi.org/10.2166/ws.2017.053



# Water-supply infrastructure of Byzantine Constantinople

## Kate Ward, James Crow and Martin Crapper

### Introduction

Modern water-supply systems – hidden beneath the ground, constructed, expanded, adapted and repaired intermittently by multiple groups of people – are often messy and difficult to comprehend. The ancient water-supply system we consider here is no different - and perhaps even more complex as it was developed over 1200 years and then had a modern city built on top. Despite this, we are beginning to understand how one of the Roman world's most important cities provided its population with water.

The remains of water infrastructure in Constantinople attest to a complex system of water-management and distribution, one that developed from the colony of Byzantium, through the growth and eventual decline of the new capital of the Roman empire, until conquest by the Ottomans. Aqueducts -- the system of channels, bridges and tunnels designed to carry water through the landscape -- were the focus of infrastructure investment in earlier periods, but cisterns for the storage and distribution of water were constructed throughout the time of Byzantine Constantinople. While recent archaeological studies have ensured a better understanding of the key elements of the system,[1] they have not investigated how the water was distributed within the city. The present study, part of the research programme "Engineering the Byzantine water supply: procurement, construction and operation", aims to apply contemporary civil engineering techniques to elucidate city's hydraulic infrastructure.[2] Much of our knowledge of hydraulic delivery and distribution in ancient urban settings derives from cities such as Pompeii and Ephesos where the infrastructure is accessible,[3] rather than

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[1] C. Mango, "The water supply of Constantinople," in id. and G. Dagron (edd.) *Constantinople and its hinterland* (Aldershot 1995) 9-18; K. Çeçen, *The longest Roman water supply line* (Istanbul 1996); J. Crow, J. Bardill and R. Bayliss 2008, *The water supply of Byzantine Constantinople* (London 2008).

[2] A parallel study is considering the application of construction management techniques to determine the processes of construction and issues concerning procurement and the workforce; see J. R. Snyder, L.C. Stephenson, J.E. Mackie and S.D. Smith, "Agent-based modelling and the Byzantine: understanding the construction of antiquity's largest infrastructure project," in P.W. Chan and C.J. Neilson (edd.), *Proc. 32nd Annual ARCOM [Assoc. of Researchers in Construction Management] Conference* (Manchester 2016) vol. 2, 963-72.

[3] Cf. D. Keenan-Jones, "Somma-Vesuvian movements and the water supply of Pompeii and the Bay of Naples," AJA 119 (2015) 191-215 for a recent study of Pompeii; for the ceramic pipe network from Ephesos and how distribution changed over time, cf. J. Pickett, "Temples, churches, cisterns and pipes: water in late antique Ephesus," in G. Wiplinger (ed.), *De aquaeductu atque aqua urbium Lyciae Pamphyliae Pisidiae* (BABesch Suppl. 27) 297-312 – in contrast to other more traditional aqueduct studies in S Turkey reported in the same volume.

from Rome or Istanbul where modern development obscures the ancient city.[4] By adopting an engineering perspective, we aim to counter the fragmentary nature of the archaeological evidence, integrating the scattered evidence into a functional whole.
The water supply in Constantinople had three distinct elements: two aqueducts (the Hadrianic Line and the Valens Line) and cisterns of varying sizes throughout the city; this use of cisterns as a major component of the supply system is singular, if not unique, in Roman municipal water supplies.[5] The available evidence varies across the three elements. Since the Hadrianic Line has no physical evidence and very few references in historical texts; we have to build up a picture of the line using what can be inferred from the topography of Constantinople and the known and likely users of this water line; we can also make inferences from the Ottoman supply system, which is thought to have made use of the same water source in the Belgrad Forest. There is more physical evidence of the Valens Line although its interpretation is uncertain, particularly along the ancient main street, the Mese. For cisterns, the evidence is both physical and textual, previous studies having provided detailed descriptions and dating of some, but we will arrive at considerably more cisterns than has been supposed by comparing and combining the two most recent and comprehensive studies. While our understanding of how the elements of the water-supply system evolved and operated is still at an early stage, the work detailed here provides a springboard for further investigation and clarifies the questions that can be asked about the Byzantine city's water supply.

## Background

Constantinople was an important new city with a water problem. Despite the strategic advantages of its location, the city that became the capital of the Roman Empire was soon compared to a beautiful woman bedecked with jewels but thirstier "than those who are dressed in rags".[6] To tackle the issue, the city undertook several challenging construction projects which added water-supply infrastructure to the existing 2nd-c. Hadrianic Line of Roman Byzantium. Within a few decades of Constantinople's foundation, engineers constructed the Valens Line to tap distant springs in the Thracian hinterland. An initial study, identifying and mapping this far-reaching aqueduct, estimated the length of channel to be 292 km, but more recently studies have calculated

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[4] See the integrated study from Roman Barcelona, albeit on a lesser scale: H.A. Orengo and C. Miró i Alaix, "Reconsidering the water system of Roman Barcino (Barcelona) from the supply to discharge," *Water History* 5 (2013) 243-66.

[5] For a review of Roman and Byzantine cisterns in the E Mediterranean region, see C.A. Stewart, "The modular design of Early Byzantine cisterns and reservoirs," in *Against gravity* (a symposium held in March 2015 at the University of Pennsylvania; prior to publication it is available at http://www.sas.upenn.edu/ancient/publications.html). In *Du Nil à Alexandrie: histoire d'eaux* (Paris 2011), I. Hairy provides an important study of the river-filled cisterns of Alexandria ranging in date from the Roman to the Islamic.

[6] Themist. *Or.* 11.151a-152b, quoted in Crow, Bardill and Bayliss (supra n.1), 224.

much greater distances.[7] The initial research on the Valens Line was followed by extensive fieldwork which identified two distinct phases of aqueduct building:[8] the first, dated to the mid-4th c., collected water from sources some 65 km from the city; the second, dated early to mid-5th c., came from sources around 120 km away, yet the straight-line distances do not give a clear picture of the scale of construction and the most recent investigation calculates the length to be at least 426 km, possibly as much as 564 km.

However, it would appear that even these substantial infrastructure investments were insufficient to supply the growing city. In the mid-5th c., with construction of the second phase of the Valens Line under way, the city altered its strategy and started to construct major cisterns within the walls.[9] With at least 8 large public baths,[10] the city may appear to follow the Roman model of extravagant water use, but the way in which the water-supply system developed and evolved points to a shortage in local water supplies. The investment in and protection of the water-supply system should be viewed as critical to the city's success.

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[7] Çeçen (supra n.1). In *Construction requirements of the water supply of Constantinople and Anastasian Wall* (Ph.D. diss., Univ. of Edinburgh 2013) 199, J.R. Snyder, based on re-analysis of the line drawn in Crow, Bardill and Bayliss (supra n.1), gives 454km.

[8] Crow, Bardill and Bayliss ibid. 26-27.

[9] The first major cistern recorded was the Modestiaca, in 363-369. Its location is uncertain, although it is possibly associated with the Saraçhane cistern identified by P. Forchheimer and J. Strzygowski, *Die Byzantinischen Wasserbehälter von Konstantinopel* (Vienna 1893) 52.

[10] M. Mundell Mango, "Thermae, balnea/loutra, hamams: the baths of Constantinople," in P. Magdalino, and N. Ergin (edd.), *Istanbul and Water, (*Anc. Nr. East. Studies, Suppl. 47; Leuven 2015) fig. 12 with pp. 138-144.

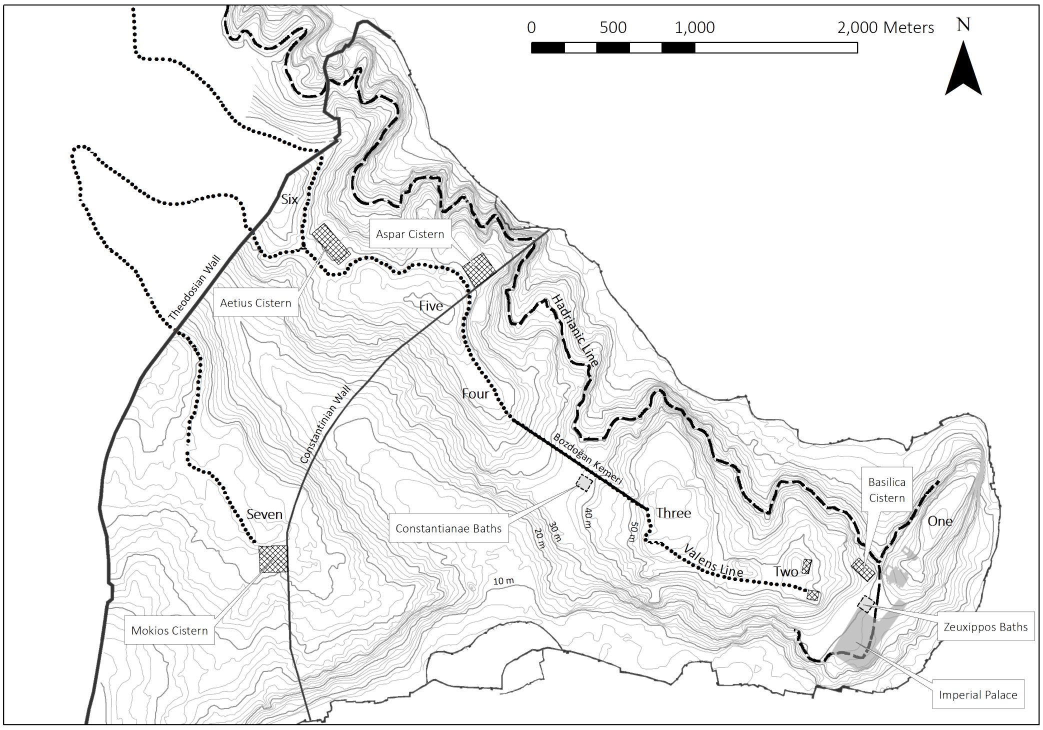

Figure 1: Original aqueduct routes proposed by Crow, Bardill and Bayliss 2008 (supra n.1). The Hadrianic Line is dashed; the Valens Line is dotted (image is adapted from the original data).

*Current understanding of the three main elements of the water supply system*

Prior to the present study, little work had been done considering water-supply at a system-wide level. The first attempt to map the two aqueduct lines within the city was made by J. Crow, J. Bardill and R. Bayliss.[11] In that study, Bayliss projected the Hadrianic Line based on access to the Basilica Cistern.[12] The modern contours of the city were utilized to trace the line back towards the Theodosian Wall. The route followed the north flanks of Hills Two, Three, Four, Five and Six and crossed the Wall at an elevation of about 35 masl). There are some inconsistencies between their written description of this route and what is illustrated.[13] In the illustrated route shown by the dashed line in fig. 1, the line is at a low point of 24 m asl in the vicinity of the Basilica Cistern before climbing *uphill* to cross the platform between Hills One and Two to the Imperial Palace. We conclude that the route suggested is too low to supply water to the Imperial Palace, and would only be able to fill the Basilica Cistern to a depth of about 3 m.

The Valens Line (shown by the dotted line in fig. 1) was drawn by Bayliss based on the location and orientation of the Bozdoğan Kemeri (the 970-m-long bridge spanning Hills Three and Four that still stands in Istanbul), the modern contours, and the location of some of the larger cisterns.

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[11] Crow, Bardill and Bayliss (supra n.1) 110-124.

[12] The Hadrianic Line is associated with the Basilica Cistern at Mal., *Chron.* 18.17, and *Chron. Pasc.* 618-19, (both quoted in Crow, Bardill and Bayliss 232).

[13] Crow, Bardill and Bayliss ibid. maps 12-15, 114-117.

In the study of 2008, Bardill compiled a bibliographic concordance of cisterns, detailing 161 examples that were identified and discussed in the literature. His work is complemented by the recent work of K. Altuğ who, with the aid of the Istanbul municipal archive (Koruma Bolge Kurulu), compiled a catalogue of 158 cisterns.[14] Both these works considerably expanded the number of cisterns known, but even recent articles continue to underestimate the significance of cisterns in the city.[15]

### Aqueduct of Hadrian

Before it became Constantinople, Byzantium was fed by an aqueduct constructed under Hadrian[16] in the 2nd c. This aqueduct was the main water-provider for the city of Constantinople until 373 when the Valens Line started bringing water in. Although no recognisable traces of the Hadrianic Line survive, it continued to serve an important rôle within the Byzantine city; the law codes from *c.*440 restrict the use of the aqueduct to "the public, hot and cold baths and [the imperial] palace"; in the 6th c., the Hadrianic Line is associated with the construction of the Basilica Cistern.[17]

#### *Water Supply to Byzantium*

Given that the Hadrianic Line served the city for such a long period of time, it is worth considering the form of the town that the aqueduct originally supplied. That the aqueduct was operated, repaired and maintained for such a long period indicates that the channel was still relatively accessible despite the enormous changes taking place around the coastline and to the peninsula's topography. The original town occupied the end of the peninsula that would become Constantinople, bounded by a defensive wall that crossed the second hill from coast to coast,[18] with the focus probably in the N-facing valley between Hills One and Two around the harbour and Strategion (now occupied by Sirkeci Station). This area is relatively low lying and could be served by an aqueduct arriving at *c.*31 m asl. Conventionally, water provided by Roman aqueducts would be distributed from the highest point of the town, maximising the area supplied. For Byzantium, this would have been at *c.*55 m asl, at the point which later became the Forum of Constantine. To achieve this, the Hadrianic Line would require a major bridge or inverted siphon to cross the valley between Hills Three and Four (where the Bozdoğan Kemeri stands), but no evidence has been found or is attested in ancient accounts. If the population of Byzantium was concentrated on the lower slopes, a crossing structure, both costly and (since it exposed a vital lifeline into

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[14] In *İstanbul'da Bizans Dönemi Sarnıçlarının Mimari Özellikleri ve Kentin Tarihsel Topografyasındaki Dağılımı.*(Ph.D. diss., İstanbul Teknik Üniversitesi 2013), K. Altuğ documented physical remains that he visited and those no longer extant, which others have investigated.

[15] In "Use of cisterns during antiquity in the Mediterranean region for water resources sustainability," *Water Science and Technology: Water* Supply 14 (2014) 38-47, L. Mays gives the number of cisterns in Constantinople as 70.

[16] See Crow, Bardill and Bayliss (supra n.1) 10-13 on attributing the aqueduct to Hadrian.

[17] *CJ* 11.42.6; Mal., *Chron.* 18.17, both quoted in Crow, Bardill and Bayliss ibid. 227, 232.

[18] C. Mango, *Le développement urbain de Constantinople (IVe-VIIe siècles)* (Paris 1985) 14.

the town) a security weakness, may have been considered unnecessary. Nonetheless, it is likely that the builders aimed for as high an entry point to the town as practical, making the crossing of the valley between Hills Three and Four critical. As the lowest ground level of this valley is estimated to have been *c.*35-36 m asl in the Byzantine period,[19] a probable maximum invert level (lowest point of the channel or pipe in cross-section) at this point is 34 m asl, assuming a cut-and-cover type construction rather than a method which would expose the channel above ground, making it vulnerable to tampering.

### *Supplying the Imperial Palace and Zeuxippos Baths*

When we come to early Constantinople, the law code from 440 states that the Hadrianic Aqueduct fed, amongst other sites, the Imperial Palace[20] which was located on the S side of the platform between Hills One and Two. The maximum ground level is *c.*30 m asl where the palace lies adjacent to the Hippodrome and Zeuxippos Baths, with ground levels falling to the south and east, so that if the channel was at a level sufficient to supply the platform level it would have been capable of supplying the Imperial Palace. Although there is no text linking the Zeuxippos Baths and the Hadrianic aqueduct, it appears clear that this is how the baths were supplied with water, which adds further evidence to the route of the aqueduct within the city; the Zeuxippos Baths, a centrepiece of the city, would have required access to an aqueduct to provide sufficient water.[21] The Baths' origins are unclear, some texts attributing the baths to Severus and others to Constantine, But in either case they are undoubtedly an early feature of the city and should therefore be linked to the Hadrianic, not the Valens Line.[22] The baths lie adjacent to the Hippodrome at a level of 30 m asl,[23] dropping slightly to the east. If this is the ground level in the baths, we would expect the water-supply to arrive at a higher level - at least 32 m asl – to allow it to flow through boilers, operate fountains and possibly showers.

### **Supplying the Constantianae Baths**

It is less clear-cut but still possible that the Hadrianic Line may also have supplied, or been intended to supply, the Constantianae Baths which are believed to lie near the

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[19] The level from W. Müller-Wiener's (*Bildlexikon zur Topographie Istanbuls* [Tübingen1977]) older map, using the contours of the 1920s, is 41 m asl. In sounding B R.M. Harrison *Excavations at Saraçhane in Istanbul* (Princeton, NJ 1986) 13-14, found the foundations of Bozdoğan Kemeri to be 6.5 m below the existing ground level.

[20] *CJ* 11.42.6, quoted in Crow, Bardill and Bayliss (supra n.1) 227.

[21] As A.T. Hodge, *Roman aqueducts & water supply* (2nd edn. London 2002) 000 said, many Roman aqueducts were constructed in order to supply public baths; a more convenient, flowing supply was merely a side benefit. Cf., e.g., the restoration of the *Aqua Marcia* and construction of the branch *Aqua Antoniniana* for the Baths of Caracalla: J. DeLaine, *The Baths of Caracalla* (JRA Suppl. 25 1997) 16.

[22] Mundell Mango (supra n.10)136.

[23] S. Casson, D. Talbot Rice and A.H.M. Jones, *Preliminary report upon the excavations carried out in the Hippodrome of Constantinople in 1927 on behalf of the British Academy* (London 1928) 21.

modern Belediye building[24] in the valley between Hills Three and Four. Construction of these baths began in 345 whereas the aqueduct of Valens did not arrive at the city until 373, and it is implausible that construction would start so far in advance of the water-supply on which the baths were reliant. Even the time to conceive, design and build the enormous Caracalla baths in Rome was no more than 7 years.[25] It seems more likely that the baths were constructed only where an adequate supply of water could be guaranteed, and when construction started, this could only have been the Hadrianic Line. In the event, however, the baths were not completed until 427. The 80-year construction period is extraordinary and must cast some doubt on the Hadrianic Line being the eventual supplier to the working baths. Still, whatever the circumstances of the baths' construction, we must consider the baths being fed by the Hadrianic Line as a strong possibility; the alternative is a bath that was intended to have been completed sat unused and empty for 20 years before the arrival of the Valens Line. Accepting, then, that the Hadrianic Line was capable of supplying the Constantianae Baths means that the channel crossed the valley between Hills Three and Four at a relatively high level. This opens up the possibility that the channel crossed the saddle of the valley and followed a course on the southern flanks of Hills Two and Three.

### *The comparative evidence of the Ottoman System*

The generally held view is that the source of the Aqueduct of Hadrian was water from the Belgrad Forest north of the city. The same region would be used by the Ottomans for the water-supply line known as Kırkçeşme. If the Ottoman system exploits the same source and (as possible traces of older structures in bridges on the Kırkçeşme Line suggest) a similar route into the city, an examination of the newer system should provide insights into the older system.[26] Maps show the route the later system took within the city and identify fountains and control towers[27] which we can use to examine the water level during Ottoman times and which can serve as a proxy for the Hadrianic Line. The Ottoman system operated as a locally pressurised system, with water being driven through pipes by gravity between control towers called suterazi; thus a series of inverted siphons distributed water through the city. This system would allow water to overcome localised obstructions and changes in level.[28] As the system was still operating under gravity, however, the overall water level dropped as it was moving from upstream to downstream. This meant that fountains and other structures with a free water surface (i.e. not under pressure within a pipe) could not be at a higher elevation than the free water surface further upstream.

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[24] C. Mango (supra n.18) 41.

[25] DeLaine (supra n.21) 183.

[26] Tursun Bey, *The History of Mehmed the Conqueror;* Gilles, *De Bosporo Thracio, Libri III, 2.3,* both quoted in Crow, Bardill and Bayliss (supra n.1) 242-43.

[27] Maps of all the Ottoman systems are reproduced in K. Çeçen (ed. C. Kolay), *İstanbul'un Osmanlı Dönemi Suyolları* (Istanbul1999).

[28] A.F. Andréossy, *Constantinople et le Bosphore de Thrace, pendant les années 1812, 1813 et 1814, et pendant l'année 1826* (Paris 1828) pl.2, with J. Crow, "Water and the creation of a new city," in Magdalino and Ergin (supra n.10) 111-24.

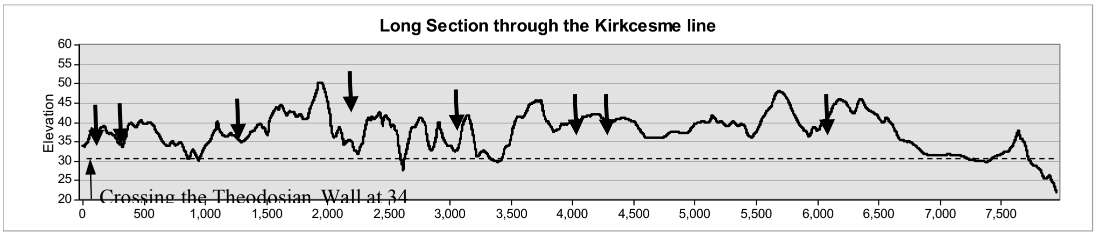

Figure 2: Ground profile through the Kırkçeşme line within the city, from the crossing point at the Theodosian Wall (left) towards the Topkapı (right) using a digitised version of Çeçen's 1999 map on a 3D model of the city based on contours from Müller-Wiener's 1977 (supra n.20) map. Arrows indicate approximate locations of çeşme (fountains) that are positioned above the 34-m crossing level at the Wall.

The maps of the Kırkçeşme system are puzzling. The crossing point near the Theodosian wall is at *c.*34 m asl, and photographs indicate that the water has a free surface at this point[29] (i.e. not under pressure), yet much of the downstream network on the Kırkçeşme line is higher than 34 m asl. The long section in fig. 2 shows the variation in ground level along the route of the main Kırkçeşme line from the Land Walls to the east of the Topkapı Palace; several fountains along the route are higher than the established 34-m baseline, an arrangement that is physically impossible and leads us to question some of the assumptions made regarding the system. Given that much of the route within the Land Walls is above an elevation of 34 m,[30] we must conclude that the structure at the crossing of the Land Wall is either a branch off the main line or has been located on maps incorrectly. The water must arrive at a higher elevation than was previously believed. This therefore removes the constraint of assuming that the Hadrianic Line also arrived around this level, and we can progress with the assumption that the Hadrianic Line reached the city at an elevation above 34 m.

### *City routes – Hill Three – northern, southern or both – the Tezgahçılar Kubbesi structure*

The next question is the route taken after the channel crossed the valley between Hills Four and Three. Previously[31] the Hadrianic Line was drawn at a low elevation (already sitting below 30 m elevation at the valley) and could only follow the northern path, taking a sinuous route around the spurs of Hills Two and Three. However, the Ottoman Kırkçeşme system, positioned significantly higher, splits at this valley, with a branch to the north and the main line to the south, to arrive at the platform between the first two hills near the middle of the Hippodrome.[32] The shape of Hills Two and Three makes this southern route shorter and the gradient of the slopes traversed is shallower,

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[29] Çeçen (supra n.27), 104.

[30] Ground-level is an imperfect proxy for pipe inverts since pipes could be buried, but the presence of fountains on or close to the Kırkçeşme route and above 34 m in elevation indicates that the pipes were running near to the surface at these points.

[31] Crow, Bardill and Bayliss (supra n.1) Maps 14-15.

[32] Çeçen (supra n.27) Maps 30-33.

which from an engineering perspective would be easier to construct (compare the original route in fig. 3and the new route in fig. 4).

The splitting point of the Ottoman Kırkçeşme system (seefig. 3) is the Tezgahçılar Kubbesi. It has been identified as originally Roman,[33] with Ottoman repairs and alterations. Although adjacent to the Bozdoğan Kemeri, it is 15 m lower, indicating that this structure was not part of the Valens Line. Thus if the original structure was Roman, it would be associated with the Hadrianic Line. Sitting on the modern 40-m contour, the structure is buried up to its roof and is *c.*5 m deep, putting the channel invert at an elevation of 35 m asl. We believe that the Kırkçeşme system can be used as a reasonable proxy for the Hadrianic Line: as it could take the northern or southern route around Hill Three, the Hadrianic Line was also capable of taking either route.

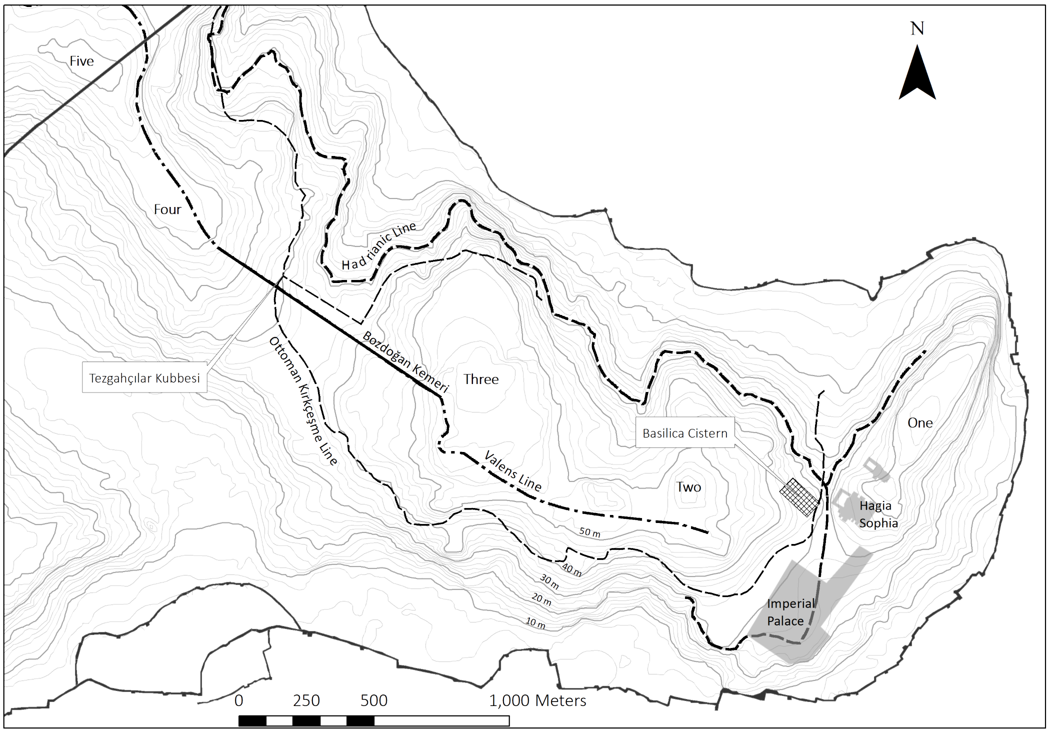

Figure 3: Hills Three and Four, the Bozdoğan Kemeri and the Tezgahçılar Kubbesi. The Ottoman Kırkçeşme line is after Çeçen (supra n.28) maps 30-33; the Hadrianic and Valens Lines shown are from Crow, Bardill and Bayliss (supra n.1) maps 12-15.

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[33] Çeçen (supra n.1) 215; Çeçen (supra n.28) 105-6; and included in Altuğ (supra n.15) 426-27 as belonging to the Early Byzantine period. Although Crow, Bardill and Bayliss (supra n.1) 116 indicate that the early dating of this structure should be treated with caution, K. Dark and F. Özgümüş, *Constantinople: archaeology of a Byzantine megapolis* (Oxford 2013) 127 with pl. 2, identify this structure as a Byzantine cistern that has been uncovered by modern work, rather than a control structure that has been buried over time. The plan included in Altuğ ibid. 427, indicates an access to the structure *c.*2.5 m below the present ground-level.

This assumption is strengthened by the indication that the Ottoman Kırkçeşme system may re-use an older structure that belonged to the Hadrianic Line.[34]

It is difficult to conclude if the Hadrianic Line split in two, like the Ottoman system, or merely crossed to the southern route. As the original town of Byzantium was not extensive and did not extend over the northern slopes of Hill Three, there would be little to justify the more complicated construction. However, this area was densely populated in the days of early Constantinople, which may have justified alterations to the existing arrangements, perhaps associated with the rebuilding of the line towards the end of the 4th c. Two of the city's 4 Nymphaea are located in regions IV and V (on the N slopes of Hill Two), and could perhaps have been supplied by the Hadrianic Line; yet even though they are located on the N slope of the hill, it would be possible for a southern branch to feed this area, as the Ottoman system illustrates.[35]

### *The Basilica Cistern: endpoint of the Aqueduct of Hadrian*

If the water supply entered the city from the N side of the peninsula and did not cross to a southern route in the valley between Hills Three and Four, the position of the Basilica Cistern becomes important: either the aqueduct ran on the slope above it, which would push the elevation up towards 40 m asl, or the Basilica Cistern was constructed on the line of the Hadrianic channel, meaning it would have run at *c.*32-36 m asl at that point, with the Basilica Cistern becoming the terminal point of the line. This carries implications for structures we believe were fed by the Hadrianic Line. Both the Zeuxippos Baths and the Imperial Palace are situated beyond the Basilica Cistern and its construction as a terminal point of the Hadrianic Line would effectively cut off their supply. We know that the Zeuxippos Baths continued to operate as baths until at least 713 and the Imperial Palace continued to be occupied, so that if the water supply was cut off considerable work would be required to re-route supplies from the Valens Line. However, this only applies if the Hadrianic Line took the northern route into the city; the southern route allows supplies to be maintained to relevant structures, including the Basilica Cistern.

During the Avar siege of the city in 626, the Valens Line was cut, preventing water from flowing until its repair in 765/6.[36] That the city survived for 140 years without this major source suggests that the flow in the Hadrianic Line was significant and also that it was accessible and capable of supplying key structures. The Hadrianic Line was not a channel that had been truncated and relegated to backup status in time of severe

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[34] It is also worth noting that the N and S branches of the Ottoman Line are unequal; the N branch, wrapping around the steep slopes of Hill Three is relatively short. On the other hand, the S branch wraps around the S slopes of Hill Two and Hill Three, and continues round to supply also the N slope of Hill Two, which may be an indication of the difficulty of construction on the N slope.

[35] For the *Notitia Urbis* and the city's districts, see B. Anderson, "Social clustering in 5th-c. Constantinople: the evidence of the *Notitia*," JRA 29 (2016) 494-508; P. Magdalino, "Neighbourhoods in Byzantine Constantinople," in F. Daim and J. Drauschke (edd.), *Hinter den Mauern und auf dem offenen Land, Leben in byzantinischen Reich* (Mainz 2016) 23-30.

[36] Theoph. *Chron.* AM 6258, quoted in Crow, Bardill and Bayliss (supra n.1) 236.

summer drought; it was a fully functioning system that enabled the city of Constantinople to survive a major attack on its infrastructure.

It would appear that, at least in later years, the Basilica Cistern was connected to the water system at its SE edge, close to the Hagia Sophia. A sluice control connected to the Basilica Cistern was reported in front of the Hagia Sophia[37] and a channel was revealed during construction of the tourist exit from the cistern in the 1980s.[38] Today, no inlets or outlets to the cistern are known. While none of this evidence is conclusive, it builds a picture of the advantages of a southern route into the city.

*Channel in the grounds of Hagia Sophia*

During excavations in the W courtyard of the Hagia Sophia, remnants of the earlier Great Church were discovered, along with a street, running roughly SE-NW which had a large 2.2 m-wide channel running beneath it.[39] Recent explorations of the tunnels and chambers beneath Hagia Sophia and its surroundings have revealed a complex network of channels (including the 2.2 m channel), although the original function of these structures remains uncertain.[40] The channel running beneath the street in the W courtyard of Hagia Sophia is generally assumed to be a sewer,[41] but our newly-suggested southern route makes it feasible to identify the channel with the Hadrianic Line, flowing northwards along the NE slope of Hill One.

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[37] Forchheimer and Strzygowski (supra n.10) 55. Gilles (K. Byrd, *Pierre Gilles' Constantinople. A modern English translation* [New York 2008] 101) reports seeing the inflow to the cistern, described as a large pipe and clearly high up the cistern wall, but does not indicate the location of the inflow.

[38] Çeçen (supra n.1) 25-27 photographed the channel, described as coming from the Hagia Sophia distribution centre, and associates the same channel with two deep wells in the grounds of the Topkapı Palace. These Ottoman structures may have been constructed around an older Byzantine-era well, as reported in H. Tezcan *Topkapı Sarayı ve Çevresinin Bizans Devri Arkeolojisi* (Istanbul 1989), 241-246.

[39] A. M. Schneider, *Die Grabung im Westhof der Sophienkirche zu Istanbul* (Berlin 1941) pl. 2. It is not clear if this channel should be linked to the channel described in n.38 above.

[40] C. Özkan Aygün, "New findings on Hagia Sophia subterranean and its surroundings," *Byzantinistica*, 2 ser., 12 (2010) 57-77.

[41] By Schneider (supra n.39) 3-4; J. Bardill, *Brickstamps of Constantinople* (Oxford 2004) 27-28.

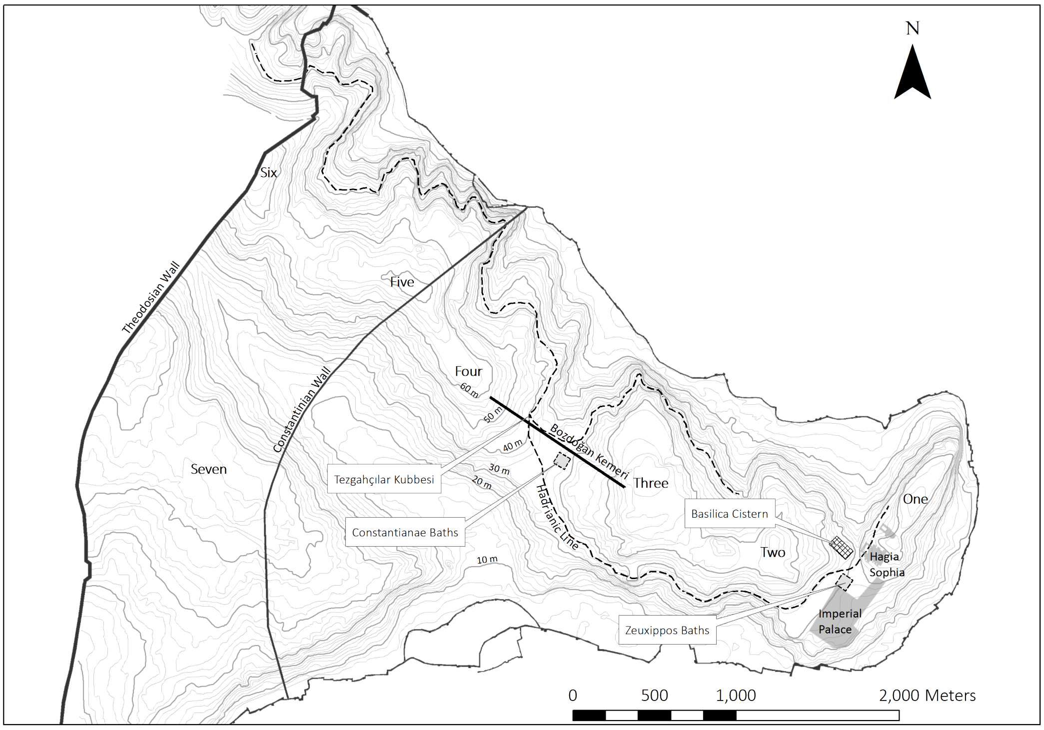

Figure 4: Suggested route of the Hadrianic Line within the city.

*Summary of suggested route of the Hadrianic Line*

- The line is probably higher than previously thought when crossing the Land Walls, as the Ottoman system levels, previously used as a proxy are inconsistent.
- At the valley between Hills Three and Four, the Hadrianic Line was at a level sufficient to cross the saddle of the valley; this opens up the possibility of a southern route into the city.
- The differences in topography of the N and S slopes of Hills Two and Three make a southern route into the city shorter and more straightforward to construct.
- At the platform area between Hills One and Two, the Hadrianic Line was high enough to feed the Zeuxippos Baths.
- The location of the Basilica Cistern and the structures known to be fed by the Hadrianic Line make a southern route into the city more favourable.

As shown in fig. 4, the route proposed for the Hadrianic Line crosses the Theodosian Wall at a level of about 39 m asl. At the valley between Hills Three and Four, the line hugs the flank of Hill Four, passing through the structure later called Tezgahçılar Kubbesi. From here, the channel may branch, with the main branch being the southern one which traverses the valley and follows the contours on the S flanks of Hills Two and Three, bringing water to the head of the N-facing valley around the harbour. When the town became Constantinople, this southern branch continued to supply many of the key sites in this part of the city, and a northern branch may have been added, extending from Tezgahçılar Kubbesi into the densely populated flanks of Hill Three.

## Aqueduct of Valens: supply to the new city

The Aqueduct of Valens was built in two phases during the early days of the new city when not only the population was increasing but also the area occupied by the city was expanding. This expansion generally moved upwards and outwards from the old city of Byzantium, incorporating a number of hills that could not be served by the Hadrianic Line. Maximising both the elevation of the channel and the area served would have driven the choice of route for the new line. The engineers would aim for a route that minimised the length of the channel and the complexity of construction. The Valens Line was constructed before the cisterns associated with it: the line arrived in the city in 373 and the first major cistern, the Aetius Cistern, was constructed in 421. We do not know whether the cisterns were planned in advance and influenced the aqueduct route but, as they had to be connected to one of the aqueducts in order to be filled,[42] it is reasonable to assume some degree of proximity between cistern and aqueduct. The siting cisterns would have been influenced by a number of factors, however, including available space, topography and downstream connections. Thus we should exercise caution in using the location of a cistern to define the location of the aqueduct.

### *Evidence for the route*

Although there is more physical evidence that may be associated with the Valens Line than there is with the Hadrianic, the interpretation of some of this evidence is difficult. The most obvious (still-visible) evidence is the aqueduct bridge crossing the valley between Hills Three and Four. Now called Bozdoğan Kemeri, it is a clear indication the aqueduct followed a route along the high ridge of hills within the city. Once thought to carry the Hadrianic Line, the bridge has been confirmed as belonging to the Valens Line.[43] Although the ends of the bridge have been lost, we have its alignment and channel elevation (57 m at the W end).[44] The remaining physical evidence is more scarce and less conclusive. A recently discovered channel upstream of Bozdoğan Kemeri might be associated with the line. A number of brick channels, stone channels and marble pipes observed along the modern Ordu Caddesi and Divan Yolu Caddesi align closely to the ancient main street of the city, the Mese, but these structures have not been subject to detailed study, some being identified as water channels, some as drainage structures.

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[42] The volume of most cisterns is too large to be fed exclusively by a rainwater-harvesting system, as the catchment area required to provide worthwhile amounts is so large as to be unfeasible.

[43] Following K.O. Dalman, *Der Valens-Aquädukt in Konstantinopel* (Bamberg 1933). In 1985 C. Mango (supra n.18) 20 suggested attribution to Hadrian, but was more cautious in 1995 (supra n.1, p. 12.) See Crow, Bardill and Bayliss (supra n.1), 13-14 for dating and attribution.

[44] Measured at arch 1 by Dalman ibid., quoted in Crow, Bardill and Bayliss (supra n.1) 120.

### *Channel in Baş Müezzin Sokak*

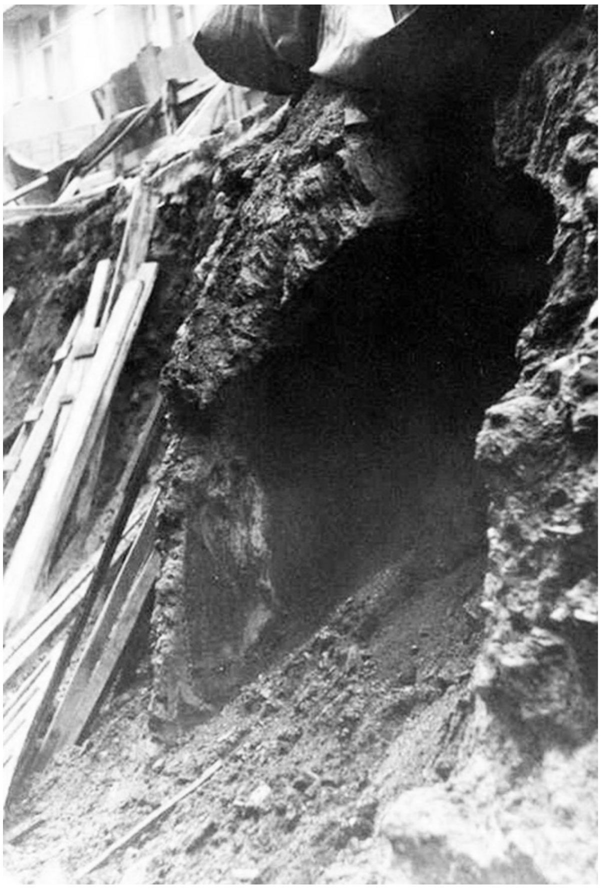

Figure 5: Channel found beneath Bas Muezzin Sokak (Istanbul Municipal Archive)

A large vaulted brick channel,(figs. 5 and 8) running perpendicular to Baş Müezzin street is a strong candidate for the Valens Line upstream of Bozdoğan Kemeri.[45] The channel is at the highest point of the street, close to where it crosses Boyacı Kapısı Street. At just over 2 m wide and *c.*2.5 m tall, the brick channel was capable of carrying high flows. Hydraulic mortar (which would be evidence of the channel being part of the aqueduct) is not recorded, but the channels position on top of the ridge effectively eliminates the possibility of the structure being a drain. The location indicates that the aqueduct would follow a route on the peak of the ridge or its S side, rather than the northern side as previously shown (see fig.1). The northern route around Hill Five is longer than the southern, but it does pass alongside the Aspar Cistern. We propose that the main channel took the southern route around Hill Five, and that a branch was constructed at the time of the construction of the Aspar. The ground level where the point the channel was found is high, *c.*67.5 m asl. From fig.5 it is apparent that the channel is positioned just beneath the road surface; thus we estimate the channel invert level at 64-64.5 m asl. One km farther upstream the channel must pass the saddle between Hills Six and Five, adjacent to the Aetius Cistern. As the modern ground level at this saddle is about 62-63 m asl, the channel must have crossed on a raised substructure or used an inverted siphon. Downstream from the channel in Baş Müezzin Sokak the land drops to Bozdoğan Kemeri, requiring the channel to drop some 7 m over 500 m – a rapid drop which could create undesirable flow conditions particularly directly upstream of a bridge. The sizeable cistern (38 m x 26 m) on the N flank of Fatih Camii[46] points to a solution: the channel could use this cistern as a settling basin, entering at a relatively high gradient but exiting at a gradient and level suitable for crossing the bridge. The large volume of water would provide a buffer to allow the transition from a relatively steep channel to a relatively shallow one.

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[45] Baş Müezzin Sokak lies northwest of the Fatih Camii, the site of the Holy Apostles church.

[46] The partially collapsed cistern measures at least 38 m x 26 m. It has some evidence of an inflow channel in one corner: Altuğ (supra n.14) cistern 137, pp 414-15.

### *Sewers, storm drains or water channels – resolving the evidence in proximity to the Mese*

Although vaulted channels and pipes ran below the line of the ancient Mese, their exact purpose is not immediately clear. Evidence of the pipes and channels found between Forum Tauri (Bayezit) and the Milyon are outlined in Table 1; their locations are illustrated in fig.7.

Drainage and water-supply are both gravity–fed, but the design features differ. As smaller channels feed into progressively larger ones, drainage accumulates flow like a river system, whereas water supply distributes flow from larger into smaller channels. Ideal flow conditions also differ. In water supply, maximising elevation is crucial, with the result that shallow gradients and slow velocities are normal. Drainage requires steeper gradients and faster velocities for the rapid removal of wastewater to prevent deposition and odour.

We know that the channels discovered at the Forum of Constantine and under the Arch of Theodosius (Table 1, no. 5) were at approximately the same elevation. If they were connected, the gradient between them was extremely shallow.[47] These poor flow conditions, exacerbated by the parallel channels being interconnected, make it unlikely that they were sewers carrying human waste. Both the flat gradient of the channels – if they were connected along the Mese – and the interpretation of the double channel as redundancy (allowing access for repair whilst maintaining an essential flow of water) support the hypothesis that the channels form part of the water supply. On the other hand, the position and arrangement of the channels suggest they are not water-supply infrastructure:

[IMAGE NOT INCLUDED IN PREPRINT]

Figure 6: Pipe excavation west of Kara Mustafa Paşa Medrese (DAI Istanbul) KB 2871).

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[47] E. Mamboury, "Les fouilles byzantines à Istanbul et dans sa banlieue immediate aux XIX$^{e}$ et XX$^{e}$ siècles," *Byzantion* 11 (1936) 253, assumed that the channels were drains running continuous from the Augusteon to the Lycus near the Forum Bovis and used this as a proxy for the line of the Mese. Because of the change in elevation, it is most likely that the line of the sewer was continuous but actually sloped in two directions, draining to both the east and the west, with the split located somewhere between the Fora of Constantine and Tauri.

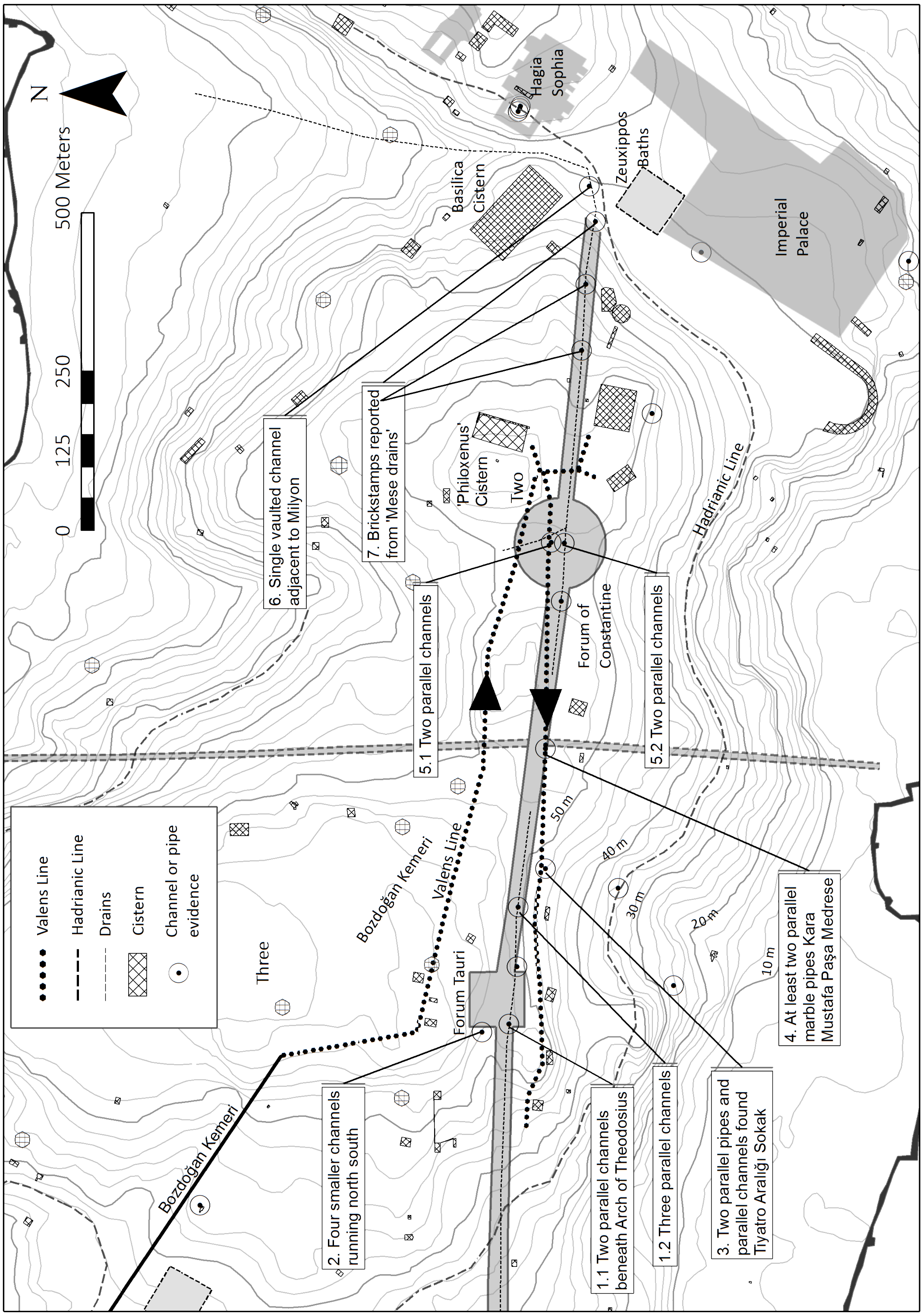

Figure 7: Detail of suggested route around the Mese for the Valens Line and the Hadrianic Line, with suggested drain routes.

# TABLE 1
# EVIDENCE OF PIPES AND CHANNELS IN THE VICINITY OF THE MESE
(see fig.7 for precise locations)

| *Ref* | *Location* | *Description* |
|---|---|---|
| 1 | Forum Tauri | The excavations of the Theodosian Arch in the 1920s uncovered two parallel channels running approximately E-W through the Arch of Theodosius. The channels were described as possible water channels.[1] These channels are in close proximity to two further discoveries: 200 m east of the Theodosian Arch 3 parallel channels were uncovered; between these two excavations, a third found a single channel.[2] |
| 2 | Forum Tauri | An excavation slightly north of the arch revealed four channels running approximately N-S.[3] These are not of a size to be associated with the channels crossing Bozdoğan Kemeri, but could possibly be drains that discharge into the larger channels beneath the Mese. |
| 3 | Tiyatro Aralığı Sokak | Offset to the south of the line established by the channels at Forum Tauri is a series of pipes shown in a photograph of an excavation in Tiyatro Aralığı Sokak.[4] It shows large marble pipes, described as running in an E-W direction. The two-part photo also shows what may be 2 parallel channels (described in the caption as galleries) which could also be associated with the water supply. To judge from the photograph, the pipes are similar to those now found in the grounds of Hagia Sophia; the relationship between pipes and channels is not clear. |
| 4 | Near Kara Mustafa Paşa Medrese | East of Tiyatro Aralığı Sokak, the excavation in fig. 6found more marble pipes west of Kara Mustafa Paşa Medrese, running in two (possibly more) parallel lines.[5] There are no indications of channels in this excavation, although it is not clear whether it extended across the full width of the road. |
| 5 | Forum of Constantine | Two sets of 2 parallel vaulted channels discovered north and south of the Column of Constantine. One set of channels is described as constructed in brick, the other in stone.[6] The brick-built channels could perhaps be associated with the channels seen passing under the Arch of Theodosius. |
| 6 | Milyon | From Müller-Wiener and an excavation near the site of the Milyon, this comprises a single vaulted channel with a branch going in the direction of the Hippodrome.[7] |
| 7 | Various | Bricks with brickstamps removed from vaulted structures along the E end of the Mese, between Atık Ali Paşa Mosque and Firuz Ağa Mosque.[8] |

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[1] S. Casson, D. Talbot Rice and A.H.M. Jones, Second report upon the excavations carried out in and near the Hippodrome of Constantinople in 1928 on behalf of the British Academy (London 1929) 40.

[2] Müller-Wiener (supra n.20) 261, fig. 294, unmarked on the diagram but noted as D in the caption, midway between A and E.

[3] R. Naumann, "Neue Beobachtungen am Theodosiusbogen und Forum Tauri in Istanbul," IstMitt 26 (1976) 117-41.

[4] The excavation occurred in 1975; photographs are included in Altuğ (supra n.13) 42, fig. 3.15.

[5] Müller-Wiener (supra n.20) 268-69, figs. 303 and 305.

[6] E. Mamboury, "Les fouilles byzantines à Istanbul et dans sa banlieue immédiate aux XIXe et XXe siècles," *Byzantion* 11 (1936) 254.

[7] Müller-Wiener (supra n.20) 216, fig. 245.

[8] Reported in Bardill (supra n.42) 77-78 from the notes of Mamboury.

they do not take the highest route available; they flow beneath the Mese, making supply to street level difficult; and the connection with Bozdoğan Kemeri entails a 90° bend at the end of the bridge and again at the Arch of Theodosius, a needlessly complex arrangement.

We can be more certain about the pipes found at Kara Mustafa Paşa Medrese (Table 1, no. 6). Their location, slightly west of the lowest point of the ridge between Hills Two and Three, could indicate that they formed a flat inverted siphon, using pressure flow either to overcome the drop in elevation or to pass through an area with insufficient ground-cover to incorporate a channel. This would be unnecessarily complicated and costly[142] for a storm drain, particularly when there is a clear option to drain down the slope towards the sea. However, as Roman engineering situates a channel to minimise loss of elevation, additional costs for pipes and siphons are justifiable. Thus we can identify the pipe finds at Tiyatro Aralığı Sokak and west of Kara Mustafa Paşa Medrese as part of the water supply.

The channels beneath the Mese (Table 1, nos. 1, 5 and 7) are not sewers and are unlikely to be water supply. While their generous proportions are consistent with storm drains, the street collection and guttering (of which there is very little evidence) would need to be large, regular and efficient for the channels to be used at capacity.

Our solution is far from certain but it offers an arrangement of both water-supply and drainage structures that reconciles the available evidence. The channels referenced as nos. 1 and 7 and the S portion of no. 5 are assumed to be drains (fig. 7). The channel at no. 1 flows west into the Lycus or Harbour of Theodosius while the channels at nos. 5 and 7 flow east towards the Augusteon, discharging around the Prosphorion Harbour. The Valens Line is expected to maintain a position on the high ground north of the Mese, distributing water to the Cistern of Philoxenus[143] before doubling back along the Mese, initially in the channels at the N portion of no. 5, then at no. 4 in pipes whilst crossing under the road, and discharginginto a channel at no. 3 to feed the cisterns on the S side of Forum Tauri.

### *Suggested Route of the Valens Line*

Although the evidence for the Valens Line is difficult to interpret with certainty, we conclude as follows:

- Based on the discovery of a large channel in Baş Müezzin Sokak, we propose that the main route for the Valens Line was on the S side of Hill Five, although a branch to feed the Aspar Cistern is likely to have been added when the cistern was constructed in 459.
- The channels running beneath the Mese are unlikely to be the main Valens Line, which probably ran on the higher ground north of the road. However, the large stone

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[142] This forms part of our current project *Engineering the water supply of Byzantine Constantinople,* in which manpower rates from G. Pegoretti, *Manuale pratico per l'estimazione dei lavori architettonici* (Milan 1863-64) are compared for equivalent lengths of hollowed-out pipe and masonry channel.

[143] The cistern on Bab-ı-Ali street, which is identified as the Cistern of Philoxenus by J. Bardill, "The Palace of Lausus and nearby monuments in Constantinople: a topographic study," *AJA* 101 (1997) 69-75.

> pipes found midway between the Forum of Constantine and the Forum Tauri are almost certainly associated with the water supply.

In fig. 8,the Valens Line enters the city on the N slope of Hill Six at *c.*65 m asl, taking the southern route around Hill Five to the bridge between Hills Four and Three. The line follows the highest ground towards Hill Two. Inverted siphons may have been necessary to maintain maximum elevation. The largest cistern north of the Mese is the Philoxenus, which may have acted as a kind of *castellum* for the Valens Line. It is uncertain whether the Valens Line continued further east towards Hill One, but there was almost certainly a branch which crossed the Mese and fed the cisterns on the S slopes of Hills Two and Three, including the Binbirdirek cistern.

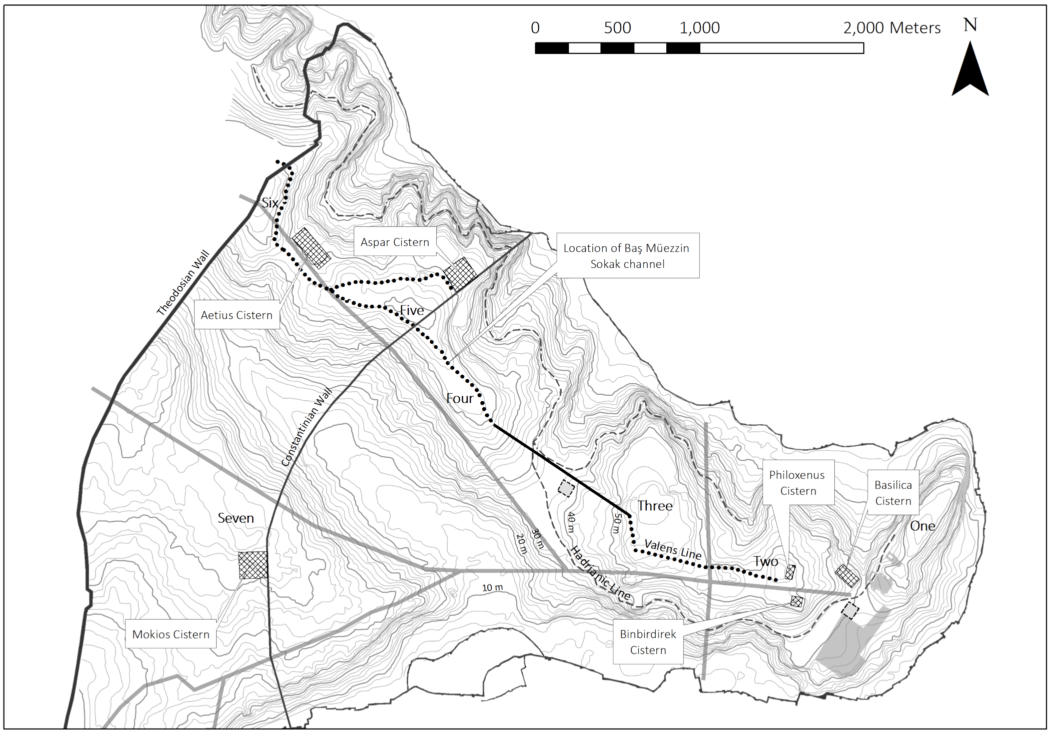

Figure 8: Suggested route of the main Valens Line

## 3. Cisterns

Scholars have long been interested in the cisterns of Constantinople, but only relatively recently have studies shown how numerous they were. This is perhaps unsurprising: although present elsewhere in the Roman Empire, cisterns were not a standard tool in water supply nor known to be combined in networks. So many cisterns marks a significant change in Constantinople's water-supply strategy, which had begun in a typical way with an aqueduct bringing water.After the construction of the colossal Valens Line, water-supply investments focused on cisterns within the city. From meeting increased demand for water by obtaining more water (as was the strategy in Rome), the strategy shifted to managing and storing available resources.

The two most recent and comprehensive works on the cisterns of Constantinople doubled the number of known cisterns in Constantinople to *c.*160.[144] By combining these studies, the current investigation has established that there are 211 Byzantine-era cisterns. This new list allows us to examine the rôle of cisterns and develop ideas about how water was distributed across the city.

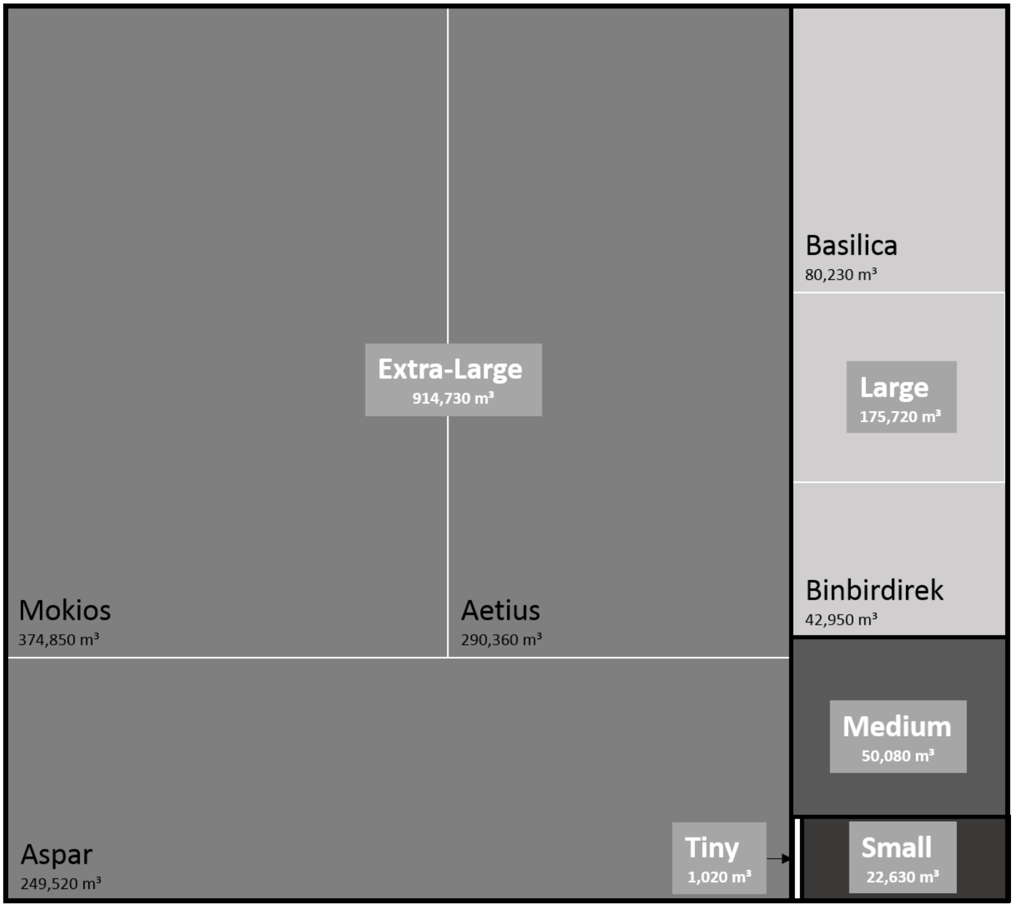

Figure 9: Distribution of known volume of cisterns (diagram created in R package version 2.4-1 [2016] of M. Tennekes, Treemap Visualization, available at https://CRAN.R-project.org/package=treemap; adapted for clarity).

### *The range of cisterns*

Cisterns in Constantinople range from the smallest, traditional structures that were probably rainwater-harvesting systems belonging to individual households, to colossal open-air structures capable of holding several months' worth of supplies. Fi illustrates how the total storage volume of over 1.1 million m³ is distributed among the 101 cisterns providing sufficient data to calculate or estimate their storage volume. Over 100 cisterns without sufficient data are omitted, including some believed to be large, such as the Modestus and Philoxenus Cisterns. The majority of storage is on the periphery of the city in the three open-air cisterns of Aetius, Mokios and Aspar; next, in the heart of the old city, come the largest of the covered cisterns, the Basilica and

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[144] In Crow, Bardill and Bayliss (supra n.1) 144-55, Bardill created a bibliographical concordance of 161 cisterns, with two of these on the Galata peninsula. Altuğ (supra n.14) 142-457 includes a catalogue of 158 cisterns on the historical peninsula.

Binbirdirek. Other cisterns add a negligible amount to the storage capacity yet clearly serve an important rôle in distributing water from the aqueducts and possibly from the larger cisterns. Fi shows the spread of cisterns across the city. It shows that there must have been a complex network of distribution beyond the main lines of the two aqueducts. The majority were constructed after the completion of the Valens Line, not to replace the aqueducts but to assist in serving the population. We do not fully understand their purpose nor how the stored resource was managed, but quantifying and locating the cisterns and the aqueducts that fed them within the city is an important first step.

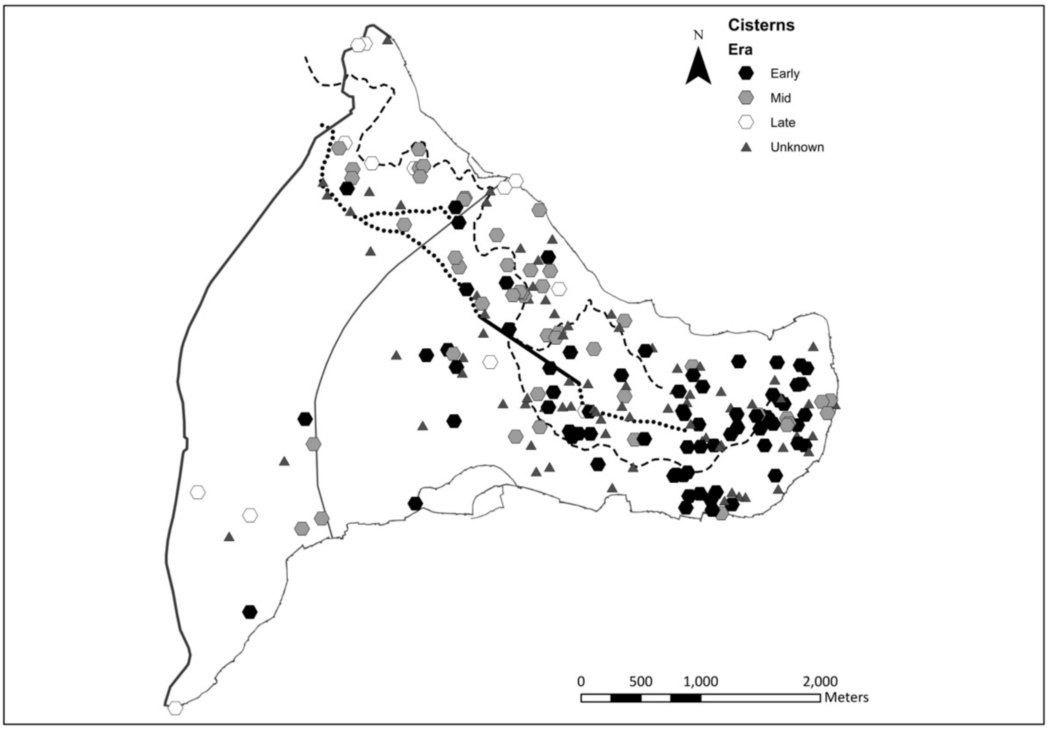

Figure 10: Distribution of early (4th-7th c.), mid (8th-12th c.), late (13th-15th c.) and unknown cisterns.

Some cisterns have been dated into three broad periods - early (4th-7th c.), middle (8th-12th c.), late (13th-15th c.) - and period unknown.[145] From this data we can see that, although cistern construction was reduced in later periods, it did continue, suggesting that the water-supply system was continuously adapted to the needs of the city as the population rose and fell, population centres moved, and cisterns were damaged. Cisterns distinguish Constantinople’s approach from that of other major Roman cities. Though space precludes detailed study of how they were connected in a distribution network, we consider the possible arrangement of cisterns and channels on a smaller scale with two cases where the need to feed cisterns raises important questions about channel routes, water sources and the use of lifting mechanisms.

Case-study 1.Water-supply to cisterns on Hill One

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[145] Altuğ (supra n.14) provides dates for some of the 158 cisterns in his catalogue. The additional cisterns from the concordance in Crow, Bardill and Bayliss (supra n.1) have been included in the “unknown period” category.

Hill One is separated from Hill Two by a valley some 10 m deep (fig. 11). Largely within the precinct of the Topkapı Sarayı, it is one of the best-preserved and least developed areas, well endowed with cisterns, some sizeable. The available catchment area is too small to sustain the cisterns using a rainwater harvesting system making it a puzzle how a substantial flow could be delivered to them. The first option is that the Valens Line crossed the valley from Hill Two to Hill One, but it is difficult to find a clear route between the hills, for this area of the city was congested with large buildings and public spaces. The shortest route is blocked by the Hagia Sophia, while the northern route is obstructed on Hill Two by the Basilica and on Hill One by the Hagia Eirene and the hospital which sat between the two Great Churches. If the cisterns were fed by the Valens Line, it probably crossed to the south of the Hagia Sophia, traversing the Augusteon before turning north by 90°. Yet this route is also congested, and the complexity of it suggests a bridge or arcade rather than a siphon. The second option is that water was lifted from a low level by a mechanised device. Such an arrangement was used during the Ottoman period in the grounds of the Topkapı Sarayı: a well was linked to a channel at a low level which fed it with water.[146] As mentioned above, the Ottoman system may update a similar Byzantine one, with the channel connecting to what we now believe to be part of the Hadrianic Line.

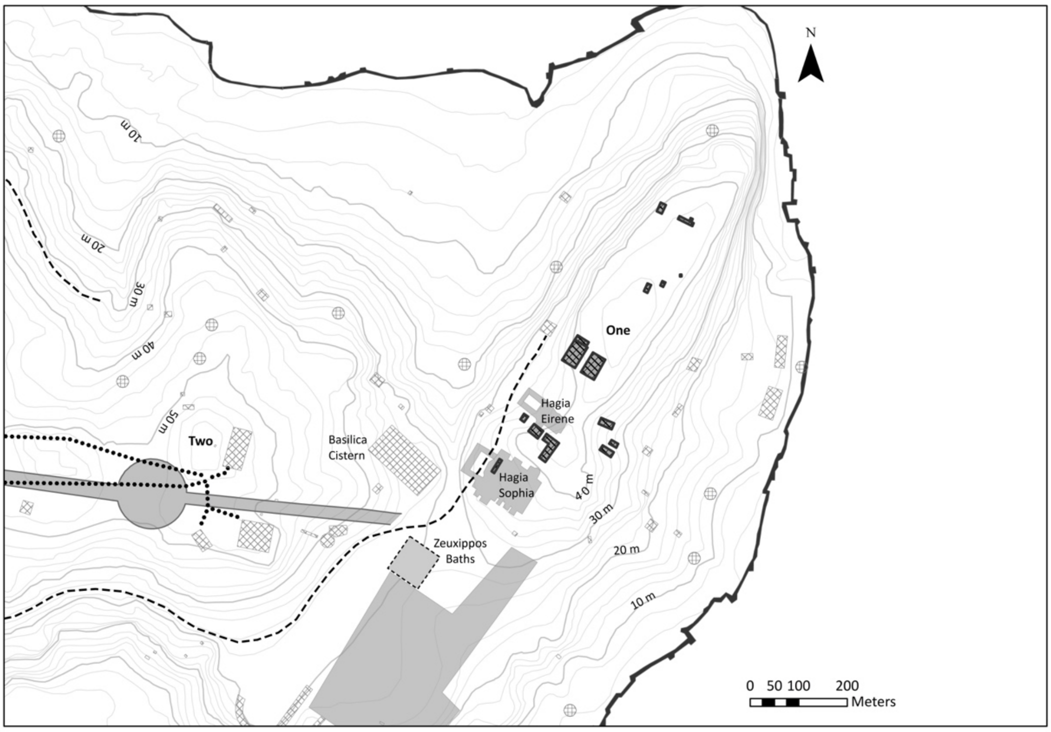

Figure 11: The water-supply to Hill One is uncertain. The cisterns highlighted are at an elevation that would require water to be lifted or to cross from Hill Two using a bridge or inverted siphon.

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[146] Özkan Aygün (supra n.40) 58; and, Tezcan (supra n.38) 241-46.

### Case-study 2. Feeding the Mokios Cistern

Mokios, an isolated open-air cistern on Hill Seven, is the largest known in Constantinople. Constructed in the early 6th c. and measuring 170 x 147 m and 15 m in depth, it provides almost a third of the known storage volume within the city. It must have been fed by an aqueduct but the aqueduct source is uncertain. Perhaps Mokios was fed by a branch from the Valens Line, splitting off close to the Aetius Cistern and following a path back out of the Theodosian Wall, crossing the Lycus valley, and then re-entering the city on the N slope of Hill Seven (fig. 1),[147] or the Lycus valley may have been crossed by an inverted siphon. Alternatively, Mokios may have been fed by a separate line taking water from the Halkalı springs. These were tapped by the later Ottoman system and are closer to the city than the Belgrad Forest or the numerous mountain springs used, respectively, by the Hadrianic Line and the Valens Line. It is difficult to conclude which option was preferred, but it seems unlikely that a water source so close to the city would go unused. Modern estimates of the yield of the Halkalı springs are relatively low,[148] and the complexity of the Ottoman systems constructed to capture them perhaps shows why the springs were not used as a primary source for the whole city, but it does not exclude them as a supply to the area around Hill Seven.

## Conclusions

Although the remaining evidence is fragmented and unclear, by considering it within the framework of a functional water-supply system that corresponds to engineering expectations we can offer a fuller interpretation of the city's water infrastructure.

We have proposed new routes for the city's aqueducts. The Hadrianic Line probably crossed from the N slopes of the peninsula to the S slopes between Hills Four and Three at a higher level, arriving close to the Hippodrome before passing the Zeuxippos Baths and Basilica Cistern. Beyond, the channel might be associated with the 2.2 m wide channel running beneath the grounds of Hagia Sophia along the NW slope of Hill One.

The Valens Line is expected to take a different route, with the main line running south of Hill Five, rather than alongside the Aspar Cistern. Farther downstream, the situation is less clear. The Valens Line probably ran north of the Mese, maintaining height before discharging into the Philoxenus Cistern. A number of branches may have crossed the Mese to feed the Binbirdirek and other cisterns on the S side, conveyed in the stone pipes found at two points near the Mese. The remaining channels running beneath the Mese could be associated with drains, although questions about their size and design remain.

Cisterns are more numerous than previously thought, with 211 associated with the Byzantine era. Their number and spread throughout the city show that they were key

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[147] Proposed in Crow, Bardill and Bayliss (supra n.1) Map 12.

[148] Dalman (supra n.43) quoted in Mango (supra n.1) 10, notes a yield of only 6000 m³ per day for Halkalı. K. Çeçen 1991 *Halkalı Suları* (Istanbul 1991) 30, noted 16 separate lines as part of the Halkalı system, with a combined flow of 4212 m³ per day.

to the operation of the system; they also show that there was a network of considerable complexity connecting the aqueduct routes just described with the cisterns, and connecting the cisterns with the people.

The extent of the water-supply system is not yet understood; some significant questions remain, particularly on how water was supplied to Hill One and to the Mokios Cistern on Hill Seven, but a detailed study of the connections between cisterns, aqueducts and the population is now possible.

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The authors express their gratitude to the Leverhulme Trust for financial support for this work under grant agreement RPG-20130410.

# The Byzantine Cisterns of Constantinople

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**Abstract**

The most unusual aspect of Byzantine Constantinople's water system was the large number of cisterns throughout the city. This research integrates the two most recent in-depth studies of the cisterns to determine that there have been at least 211 cisterns attributed to the Byzantine city. The distribution of the cisterns indicates that the size and number of cisterns constructed reduced over time, with more and larger cisterns developed prior to the seventh century. Cisterns are concentrated in the older area of the City and sparser on the periphery, but with later ones more common in the peripheral areas, suggesting that water provision was extended over time, and although the majority of cisterns are small, most storage volume is concentrated in the three largest open-air cisterns. The extended, detailed list produced will allow more in-depth investigations to proceed. Analysis of the distribution of cisterns across the City creates a framework for understanding the development and functioning of Byzantine Constantinople's complex water supply system.

**Keywords**
Constantinople; Water supply; Cisterns

## INTRODUCTION

Cisterns have been used by many ancient civilisations to store water (Mays 2014), but those in Constantinople are unparalleled in scale and number. The distribution of cisterns in Constantinople indicates the approach to water supply in Constantinople differed significantly from that of Rome. Understanding the reasons behind this alteration in strategy is one of the long term goals of our research programme "Engineering the Byzantine water supply: procurement, construction and operation". The present study investigates the cisterns, which are key evidence of the different approach used in Constantinople. These cisterns embody the change in strategy – from abundance to careful storage and management – that allowed the city to flourish as the new Rome.

Constantinople was constructed as the new capital of the Roman Empire in the early fourth century on the site of Byzantium. Located on a peninsula at the edge of Thrace, the City, as illustrated in Figure 1, was bounded by the Sea of Marmara to the south, the Golden Horn to the north and the Bosphorus to the east. Although the

City was surrounded by water, there were no substantial nearby sources of fresh water.

Figure 1: Byzantine Constantinople with main features marked, Hills of the City numbered one to seven, and the locations of 211 Byzantine era cisterns.

Initially, the city relied on the 47 km long Hadrianic aqueduct, which was constructed in the 2nd century A.D. to bring water to the town of Byzantium. However, this aqueduct alone was not sufficient for the growing city and work started in the mid-4th century A.D. on constructing a monumental aqueduct bringing water from springs in the Thracian hinterland (Çeçen 1996; Crow *et al.* 2008; Snyder *forthcoming*, 2013). This new aqueduct, the Valens aqueduct, was added to by a second phase of construction in the early to mid-5th century A.D. which brought the length of the system to at least 426 km and perhaps as much as 564 km (Ruggeri *et al.* 2016). Around the same time (the mid-5th century A.D.) the focus of water infrastructure investment switched from water collection structures outside the city to major cisterns within the city walls.

In modern times, the number of cisterns found and recorded has grown considerably. Gilles (Byrd 2008) described nine cisterns, some still in use, during his time in the city in the 1540s. The first attempt to systematically catalogue the cisterns was by Forchheimer & Strzygowski (1893). It listed, within the City, three open-air reservoirs and 40 closed cisterns, and reported descriptions of 27 sites that were unable to be confirmed. Müller-Wiener (1977) records about 75 cisterns in his study of the topography of Byzantine and Ottoman Constantinople. The most recent works are Bardill's bibliographical concordance within Crow *et al.* (2008) which lists 161 entries (including two in Sycae (Galata), north of the Golden Horn) and the cistern catalogue by Altuğ (2013) which has 158 entries. Despite these publications, even recent works, such as Mays (2014), state the number of known cisterns in the City at around 70.

As the number of cisterns known within the city has grown it has become clearer that the cisterns are central to Constantinople's water supply strategy. In fact the number of cisterns within the city is higher than even the most recent studies concluded. At first glance, the studies of Crow *et al.* (2008) and Altuğ (2013), despite using different methods for compiling their lists, appear to agree that there are around 160 Byzantine era cisterns within the city. The bibliographical concordance in Crow *et al.* (2008, 143-155, Maps 12-15) lists cisterns collected from previous studies going back to the sixteenth century, whereas the catalogue of Altuğ (2013) comprises cisterns that either still exist or have firm records and can be mapped precisely. When these two works are compared, it is clear that not all cisterns feature on both lists, some being unique to one or the other. The combination of the two sources has revealed that there is evidence of at least 211 Byzantine era cisterns in Istanbul. Of the 211 entries, 97 were present on both lists, 61 were exclusive to Altuğ's catalogue and 53 were exclusive to the concordance of Crow *et al.* (2008).

Our understanding of the water supply system is still at an early stage, but with this expanded dataset we are able to begin exploring the role of the cistern within the city, provide a foundation for future investigations and raise some of the questions that can be asked about the water supply system as a whole.

## DEVELOPMENT OF CISTERN TECHNOLOGY

Cisterns are an old technology with examples dating to the Neolithic Age. Typically these cisterns were small in scale and collected rainwater in a domestic setting (Angelakis & Spyridakis 2010; Mays *et al.* 2007). This type of cistern was also used through the Roman era, often built into the structure of a house with the roof acting as a catchment. In the Roman era larger cisterns start to be constructed, often associated with high demand users where the constant flow from the aqueduct would be insufficient to meet short term supply needs, such as the Piscina Mirabilis (12,600 $m^3$), constructed to serve the naval port at Misenum (De Feo *et al.* 2010). In Roman North Africa, the concept of storage and management of water on a non-domestic scale appears to be reflected in the larger cisterns, for example in Carthage the La Malga, Dar Saniat and Bordj Djedid cisterns, all associated with aqueduct or groundwater sources (Wilson 1998). These cisterns can bridge a short-term imbalance between demand and what the aqueduct can supply and prevent waste of this important resource.

However, it is in Constantinople that we appear to see the store and manage approach deployed across an entire city. The cisterns in Constantinople exist at scales far beyond the domestic rainwater-harvesting cisterns of Greece and in numbers far beyond those of North Africa. In Constantinople we believe that the cisterns formed a unique storage and distribution system that would have required significant operation and management to be successful.

## CISTERNS IN CONSTANTINOPLE

Our longer list of cisterns, along with the collated data on dimensions and construction period enable us to reflect on what can now be surmised about the water supply in Constantinople.

### Rainwater harvesting

Although the source of water for the cisterns of Constantinople is unverified, it is highly likely that the cisterns were fed by the two aqueducts rather than by rainwater harvesting (Crow *et al*. 2008, 140-141). The majority of cisterns in the city are far larger than those typically associated with rainwater harvesting; only 14 cisterns are known to have a volume less than 100 m³ (see the section below on the distribution of volume of cisterns). The collection areas required for the larger cisterns would be colossal, but the topography of the city, with steeply sloping spurs, and the location of cisterns, generally high up the slope, reduce the available collection area. The tendency for cisterns to be found in clusters also reduces the available collection catchment per cistern. Rainwater is likely to have been the primary source of water for the smallest cisterns in the city which we can assume are domestic cisterns not to be associated with the wider network. Rain may also have provided a secondary source of water for some larger cisterns where roofs and courtyards surfaces could be conveniently channelled.

A full calculation of rainwater harvesting potential is outwith the scope of this paper but with annual rainfall of between 630 and 730 mm estimated for the Antique period (these estimates are from a preliminary unpublished Macrophysical Climate Model study) and an estimated population of 360,000 (Jacoby 1961), the *entire* historic peninsula at approximately 13.4 million m² would only be able to provide 64 litres/person/day. Of course, the cisterns would only collect a fraction of the rain falling on the city, not all of it. As soon as we start to make this calculation more realistic (by reducing the area available for collection, assuming some losses of rainfall and taking into consideration seasonal variation) the water available per capita becomes unfeasibly small. The enormous investment represented by the cisterns was not to enable the city to just struggle along but in order to let it flourish. To do that, the cisterns must have been fed by the aqueducts.

### Cistern distribution – location and volume

Figure 2 illustrates the overall distribution across the City, with a clear concentration of cisterns along the ridge that comprises Hills One to Six. This concentration follows the likely route of the two aqueducts within the City, with the earlier Hadrianic aqueduct running half way up the northern slope from Hills Six to Two, and the later Valens aqueduct further to the south, running close to the crest and across the Bozdoğan Kemeri, again from Hills Six to Two. Given that the cisterns tend to follow the route of the aqueduct, we can suggest that the cluster of cisterns around Hill One indicates that at least one of the aqueducts extended this far. Many of the new cisterns from Altuğ's catalogue are located on the south side of the City, where few cisterns were previously known. These finds confirm the notion that cisterns were present throughout most parts of the City.

Figure 2: The City's 211 cisterns categorised by volume. Extra Large >100,000 $m^3$; Large 5,000 – 99,999 $m^3$; Medium 1,000 – 4,999 $m^3$; Small 100 – 999 $m^3$; Tiny <100 $m^3$. Numbers indicate the Hills of the City.

From Figure 2 it is apparent that there is a greater concentration of cisterns around Hills One and Two, the oldest area of the City, where the population was likely to be the highest. We know that some households had piped water supplies, based on law codes governing the size of supply pipe permitted (Codex Theodosianus 15.2.3 in Crow *et al.* 2008). Public fountains are also mentioned in the law codes and it is around fountains that people are reported to gather in times of water shortage (Procopius, *Secret History* 26.23 in Crow *et al.* 2008). So people are unlikely to live far from a cistern and there are cisterns distributed across the City, which would maximise the ease of access to water by the population. The furthest distance of any point in the City from a cistern is 1,300 m, on Hill Seven, in the zone between the Constantinian and Theodosian Walls. If considering the more populated area within the Constantinian Walls, the maximum distance to a cistern drops to just 500 m. Again, this is on the periphery, where the population density was likely to have been lower.

There is volume data for just under half of the 211 cisterns, although in some cases the depth had to be estimated from photographs. From the known data it is possible to state that the cisterns range in size from under 2 $m^3$ to over 370,000 $m^3$. It should be noted that these volumes represent the upper bound of possible storage, as there is no clear evidence that cisterns were used up to the maximum possible capacity and the depth of a cistern might have been influenced by factors other than the need for storage. The distribution of cisterns across the range is illustrated in Figure 3, where five size categories have been used. The volume of unknown cisterns should not be dismissed as trivial, with at least two cisterns thought to be very large, the cistern on top of Hill Two of which only a 90 m long section of wall remains and the Modestus cistern, tentatively identified by Forchheimer and Strzygowski (1893, 52) as a 154 m long and 90 m wide structure housing the later Saraçhane market near the Bozdoğan Kemeri.

The largest cisterns are three open-air cisterns that provide over three-quarters of the known storage volume within the city and may have a function feeding the rest of the system when inflows are low or have other purposes associated with agriculture or industry.

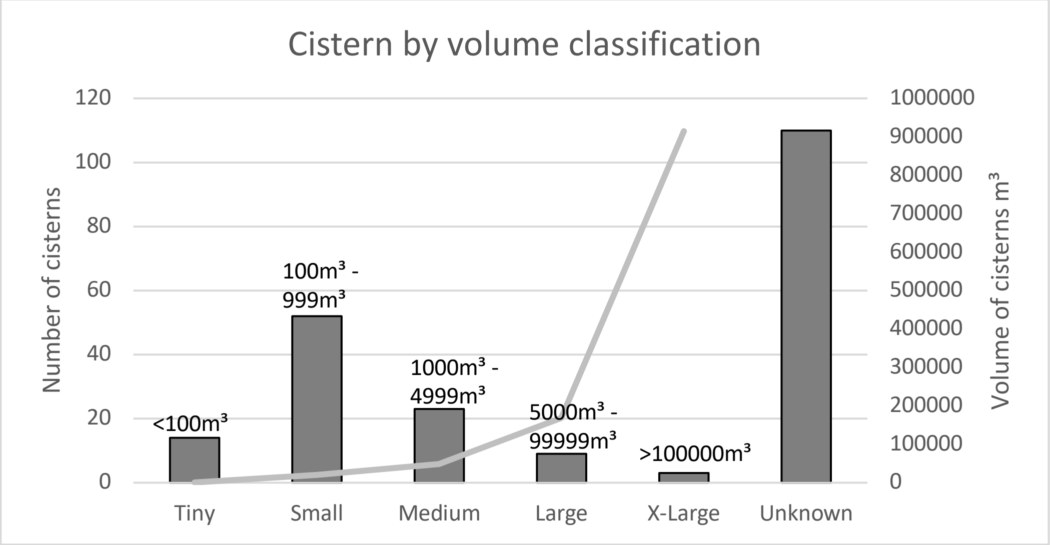

Figure 3: Number of cisterns in each volume classification

**Distribution of cisterns over time**

Most cisterns are difficult to date with any precision, some, like the Yerebatan Sarayı (Basilica) cistern, can be dated with some certainty from historical sources, although often these have different interpretations. Others may be dated from specific forms of construction, and others through the reuse of dateable architectural members which provides a *terminus post quem* for the works. Altuğ's catalogue includes volume and an estimate of the date of construction, which allows us to examine the water supply and its development more closely, although it should be noted that this is a preliminary attempt which will be supplemented by further analysis of those listed in Bardill's concordance (Crow *et al.* 2008). The attribution of cisterns by period is shown in Table 1 below and the distribution is illustrated in Figure 4.

**Table 1:** Distribution of cisterns by period

| | |
|---|---|
| Early (4th – 7th century) | 33.8% |
| Mid (8th – 12th century) | 21.9% |
| Late (13th – 15th century) | 6.2% |
| Unknown era | 38.1% |

In the early period, defined by Altuğ as the fourth to seventh century, the distribution is well-defined. The extremely large open-air reservoirs are located on the periphery of the City in the intramural area (*i.e.* between the Constantinian and Theodosian Walls) where population density was likely to be very low and space plentiful (Jacoby 1961). All the large covered cisterns are clustered in the oldest area of the City, on Hills One and Two. The size of the cisterns reflects the density of the population, which would imply a high demand for water. But the same density would preclude open cisterns, since space is at a premium. Covered cisterns can be built on, though the initial construction is disruptive. The medium cisterns are also mostly concentrated around Hills One and Two, with a few other cisterns further out, around Hills Three, Four and Five. The small cisterns are evenly spread between Hills One, Two and Three and are the only early-period cisterns on the northern slopes of Hills Two and Three.

In the mid-period, covering the eighth to twelfth century, cisterns appear throughout the city but there is a concentration of cisterns constructed on the periphery, especially on the northern slopes of Hills Four and Five. Previously there were few cisterns here, perhaps indicating that population density was higher here during this period. There is another cluster of mid-period cisterns around Hill One although their purpose is far from clear in an area already densely populated with cisterns.

The late-period cisterns also tend to be peripheral with over half located in the intramural region and the rest on the slopes of Hills Three, Four and Five.

The cisterns where the era is unknown are spread evenly across the City, with most inside the Constantinian Walls. Almost 40% of the cisterns are not attributed to a particular era, either because Altuğ was unable to determine the period or because the chronology of the cistern has not yet been systematically assessed.

There is no information available regarding if or when particular cisterns stopped being used. The fact that most of the middle and late period cisterns supply areas relatively poorly served by early-period cisterns suggests that many of the early cisterns continued to function into the middle and possibly the late period, although the question of why new cisterns continued to be built when the population is believed to have peaked during the early period remains to be answered.

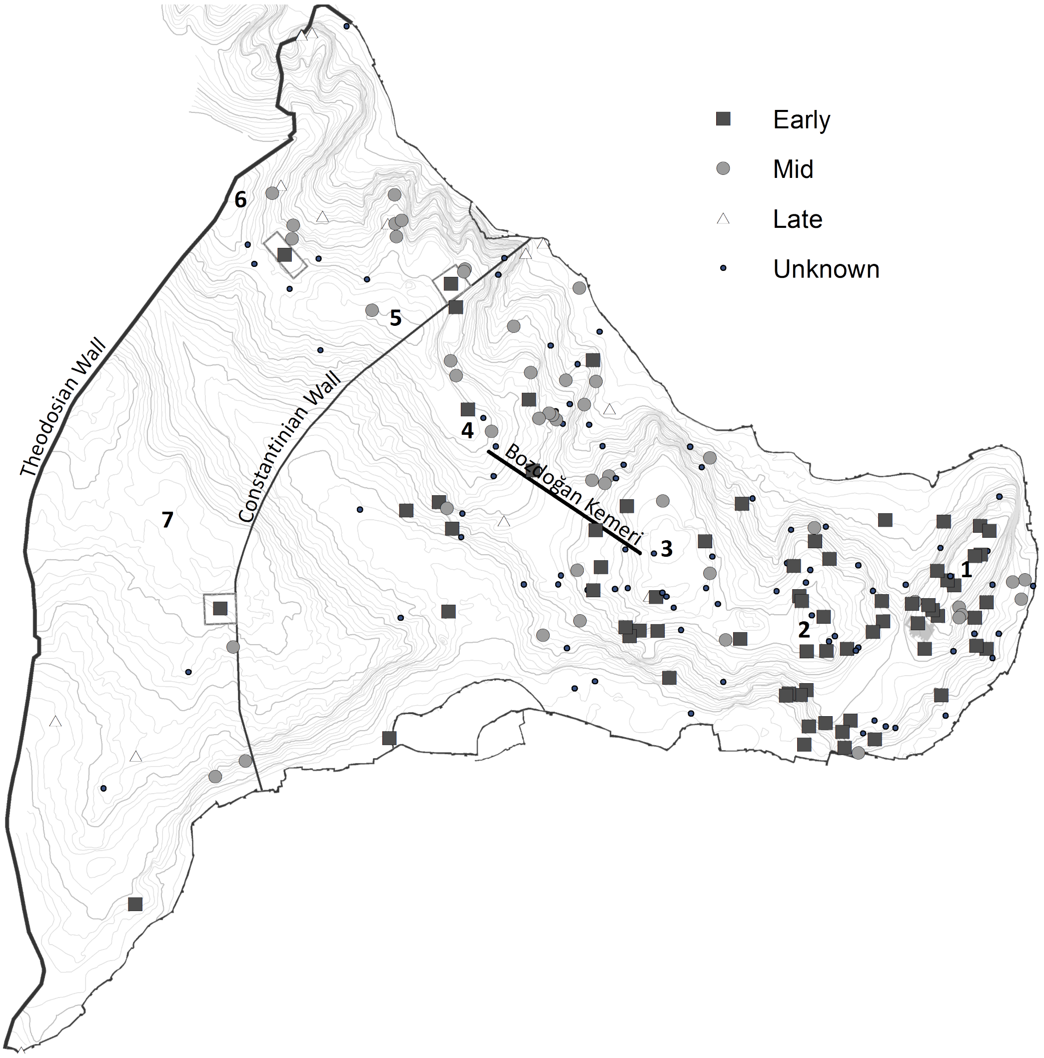

Figure 4: Cistern distribution by era: Early era (4th – 7th century) – square; Mid era (8th – 12th century) – circle; Late era (13th – 15th century) – triangle; Unknown era – dot. Numbers indicate the Hills of the City. Dating of cisterns comes from Altuğ (2013).

## CONCLUSIONS

We have established that there are three times as many cisterns as some currently report, and a third more than even the most in-depth previous research. The large number of cisterns in Constantinople are evidence that the water supply was significantly different from the typical Roman approach, being an extension of the managed storage used in Roman North Africa, also evident in Syria and Roman Mesopotamia (see Crow 2012, 41).

Studies of Constantinople's water supply can provide historians and archaeologists much insight about both everyday life in the city and the ability to use and manage technology for the benefit of citizens. The records on cistern construction period are currently basic and dimension data are only partial and unlikely to be improved much in the future. However, we are able to make some key inferences:

- The location of many cisterns on the high ground near the top of the ridge and the clustering of cisterns together substantially reduces the available collection catchment and effectively eliminates the possibility that the cisterns relied on rainwater harvesting for their primary water source.

- The distribution of cisterns in terms of location and volume suggests a complex network of storage and distribution that would have required active management to operate successfully.
- The distribution of cisterns through time illustrates a city that altered and adapted its water supply system throughout the 1000 years that it served the population of Byzantine Constantinople.

Our exploration of the full set of cisterns data also allows us to pose a number of questions which will be central to developing a full understanding of the water supply system in Constantinople:

- Why did Constantinople make such extensive use of cisterns compared with other cities in the Roman world?
- Given the number of decisions that would need to be made to divert water into the cisterns and store it there, how was this complex network managed and operated?
- How might the enormous volumes of water in the three 'extra-large' cisterns have been used?

The research programme "Engineering the Byzantine water supply: procurement, construction and operation" will use an engineering perspective to answer questions of interest to archaeologists. The conclusions drawn in this paper and the up-to-date catalogue of 211 Byzantine era cisterns will now feed into further work on the development of theoretical water networks and create further lines of enquiry into the archaeological and historical sources. Networks which connect cisterns, aqueducts and the population are now being developed to enable a more in-depth investigation into how the cisterns affected life in the Byzantine City of Constantinople.

## ACKNOWLEDGEMENT

The authors express their gratitude to the EPSRC and the Leverhulme Trust for financial support for this work under grant agreement RPG-2013-410.

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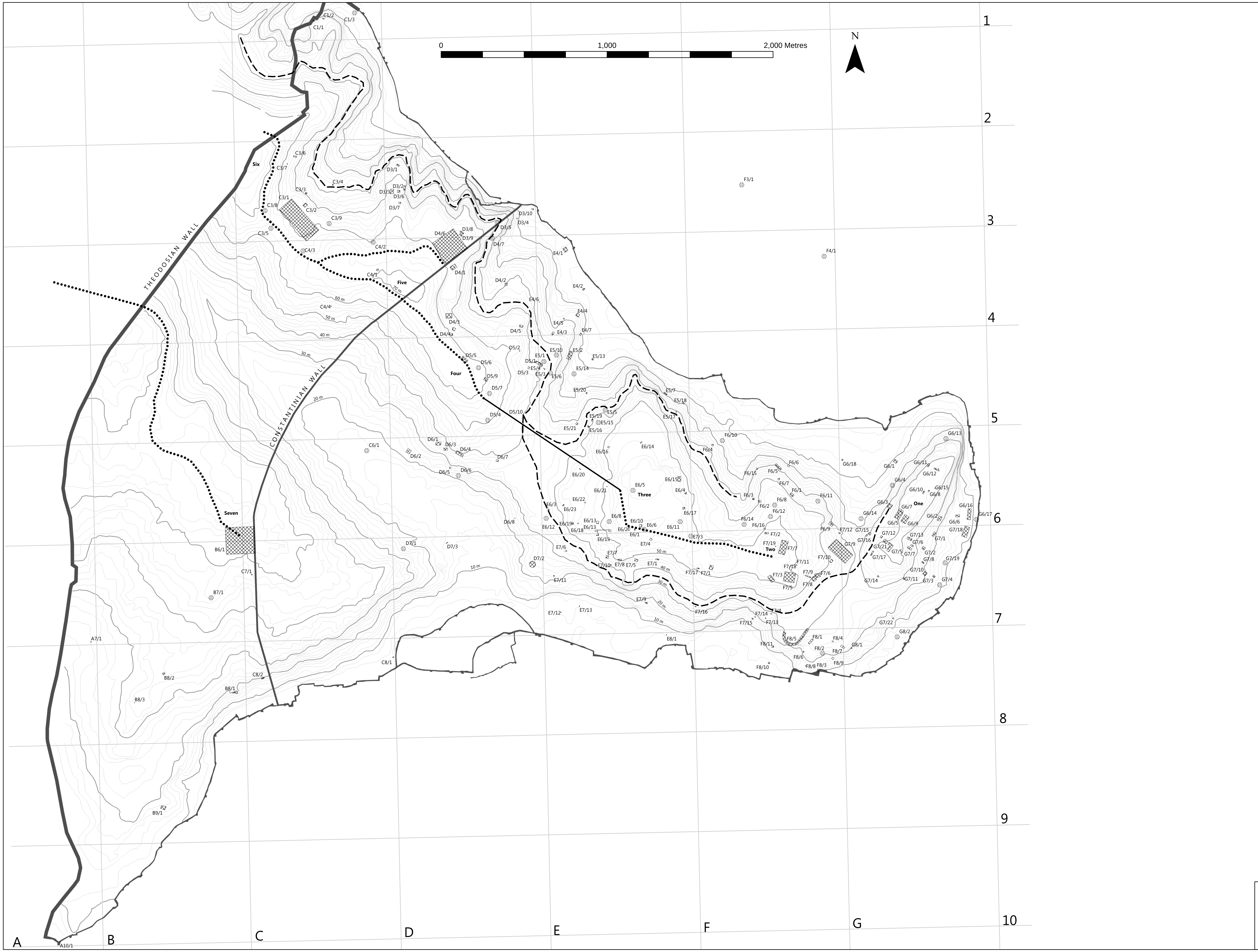

Appendix B Map
Byzantine Cisterns of Constantinople
with Aqueduct of Valens and
Aqueduct of Hadrian
March 2018
Kate Ward