

Reconstructing the water-supply system of Constantinople

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The availability of fresh water was an important concern for the Byzantine city of Constantinople. In the early second century, around two centuries before the small Thracian town of Byzantium was transformed into the new eastern administrative capital, the emperor Hadrian built an aqueduct to provide the citizens of Byzantium with fresh water (Mango 1995: 9). In the fourth century, the transformed metropolis of Constantinople had a booming population and a growing need for more water. As the Hadrianic water-supply system was proving insufficient and the surrounds of the city offered no significant local fresh-water resources, the city looked far into its hinterland to quench the thirst of its inhabitants.

The mid fourth century saw the beginning of construction of one of the longest water-supply systems in history. By the beginning of the fifth century, a second phase was completed that extended the long-distance water supply from natural springs 120km west of Constantinople to the city. Recent research (Snyder 2013) on the construction materials and workforce used in the building of the water-supply infrastructure of Constantinople has shown that it was one of the largest construction projects undertaken in the ancient world, requiring as much stone as the Great Pyramid of Giza and five times more manpower than that required to build the Baths of Caracalla in Rome.



The fifth-century monumental aqueduct bridge of Kumardere, part of Constantinople's water-supply system.

Despite its scale, the water-supply system of Constantinople has been the focus of only two major studies (Çeçen, 1996; Crow et al. 2008) and, compared to the water-supply system of Rome, it is significantly neglected in modern scholarship. From a theoretical point of view, this neglect is problematic because an improved understanding of the construction process of the water-supply system could change the longstanding narrative of deteriorating engineering and organisational skills following the decline of the western Roman empire. Amazingly, much of the water-supply system is still preserved, despite numerous earthquakes. Today, however, proposed construction projects threaten its existence and highlight the need for immediate and extensive studies to be undertaken.

As part of a two-year Leverhulme-funded project at the University of Edinburgh, we will employ agent-based simulation modelling to study the construction of the water-supply system of Constantinople. The aims of this part of the project are threefold. Firstly, we aim to integrate information from different domains (archaeological, textual, historical and ethnographic) into a coherent narrative that can be visualised in simulation models. Secondly, we aim to use simulation experiments to generate hypotheses about the day-to-day construction activities, different levels of agency and major organisational decisions taken in these levels. Finally, we aim to improve some of the earlier manpower-requirement calculations, based on the information sources we will have gathered and using geographical analyses in our simulation models.

About agent-based modelling

Agent-based modelling (ABM) is a *constructive* research approach that enables the modeller to construct a detailed hypothetical reality by generating virtual representatives of the concepts that are relevant to the study, to assign qualitative or mathematical properties to these representative entities and to define logical rules that govern, constrain or produce their behaviour and interactions.

Like other types of modelling, ABM brings about simplifications of the perceived reality (Gilbert and Troitzsch 2005). Yet, it offers a different way of simplification by enabling the study of non-linear systems dynamically and as a whole, rather than in parts. It facilitates systematic reasoning and analysis in complicated or complex settings by generating virtual elements that are thought to imitate real-life processes. Agent-based models generate many independent and interacting virtual agents that are also the primary units of analysis. These agents are 'self-contained programs which can control their own actions based on their perceptions of their operating environment' (Huhns and Singh 1998) and they can be built to represent independent and adaptive individuals or elements in a system.

Because of its unique properties, ABM has become an increasingly popular tool in the social sciences, including

economics, sociology and the interdisciplinary field of sustainability studies. Agent-based modelling is also an emerging technique for analysing social behaviour and organisation in an archaeological context. Important studies include Kohler et al.'s influential work on Anasazi populations (1996), Graham's spatial and social network analysis based on Antonine itineraries (2006) and Wilkinson et al.'s work on urbanisation in Bronze Age communities in Upper Mesopotamia (2007).

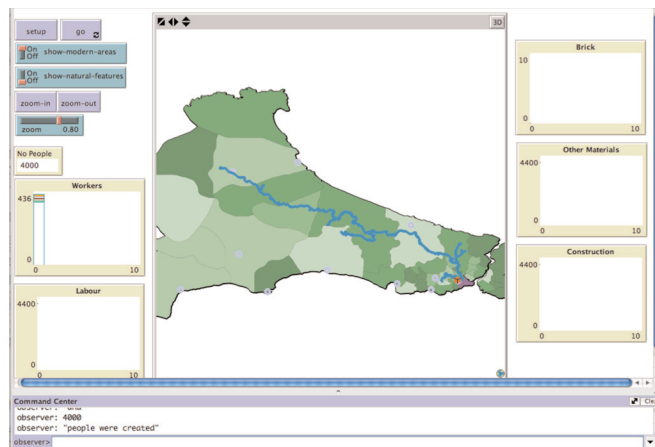
Simulating the water-supply system of Constantinople

As mentioned above, the agent-based model of the water-supply system aims to integrate information from different sources. The starting point is the structure itself, which provides a lot of information about the construction process. The structure of the water-supply system of Constantinople is made up of two primary structural elements: bridges and channels. The majority of the channel systems are built and buried immediately below ground in the 'cut and cover' method and occasionally run through rock-cut tunnels and over earthen embankments. The water-supply system traverses a landscape that changes from rolling open lowlands to densely-forested and mountainous uplands. Not surprisingly, the greatest concentration of aqueduct bridges is found in the latter, between the villages of Çiftlikköy and Binkılıç. The steep hills and deep valleys of this region also host the largest of the aqueduct bridges in the hinterland with dimensions of up to 175m long and 37m high.

The main structural materials of the water-supply system are stone (marine and crystalline limestone) and lime-based hydraulic mortar. Unlike the architecture of late antique Constantinople (with its alternating courses of brick and stone), brick was not used as a load-bearing structural element in the construction of the water-supply system. However, large quantities of crushed bricks were used as aggregate in the structural mortar and channel-lining plaster. Whereas stone was procured from sources local to the construction site, brick was most likely produced at brickyards right outside Constantinople's walls. In addition, compared with similar structures – such as other water-supply systems and fortification walls – we know that the Constantinopolitan water-supply system was most probably built in multiple simultaneously-constructed sections and that workers were employed and organised under a trade guild system.

We have started building the 'CLAWS' (Constructing the Late Antique Water Supply) model by embedding GIS data of Thrace into the simulation model. Different layers of data visualise the location of the water-supply system, the city of Constantinople, the brick factory and the known towns of the time. The next step in reconstructing the building process is the gathering of information and hypotheses about workers from different occupations, their hometowns and guild organisations. The model will support calculations of

manpower requirements, in particular in relation to material logistics, by showing the most efficient routes and organisations as a benchmark. It will also enable us to explore different scenarios related to trade guilds (size, location, spread of skills and tacit knowledge), worksite divisions (logistics of multiple simultaneous construction sites), the lives of workers (careers, working conditions, mobility) and the logistics of material supply (procurement sites, production sites, transportation networks).



The CLAWS simulation model running in NetLogo.

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