Assessing Roman large-scale hydraulic systems
Data integration for large-area research

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Conference Abstracts book

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The Değirmendere Aqueduct of Ephesus

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The Değirmendere Aqueduct of Ephesus, 36.5 km long, was the longest, but thus also the youngest of the five long-distance aqueducts that brought water to the metropolis in the province of Asia from all directions. The springs were located in the southeast of the city and the water was brought to the city over 24 bridges and through four tunnels. The first aqueduct was built in Hadrianic times. After an earthquake most of the channel was not only repaired but completely rebuilt in Antonine times.

In the central part, the remains of the structure are still visible from afar. Above ground, high above the coast, the remains of the aqueduct were cleared of dense vegetation over a stretch of 11 km so that they could be completely recorded and documented during the course of a project of the Austrian Science Fund. Here, it was possible to detect the double line along the entire stretch, of which hardly any details were known at the beginning of the project. Through the exact measurement of the gradient and with the support of the geologists, it was possible to solve a great mystery: At the site of a tectonic fault line, an earthquake caused the aqueduct to sag by 3 meters only 23 years after the Hadrianic aqueduct was put into operation. This resulted in the construction of a new channel with a larger cross-section in the Antonine times, as more springs were fed into it. As far as the bridge in the Bahçecıkboğaz Valley, the new channel lay below the old one with such a low gradient that a whole series of bypasses were discovered in this area. At this bridge, the old and the new channel were at the same level, while after that at the other side of the valley the new channel was built above the old one in order to reach the city 10 meters higher with a lower gradient and thus be able to supply higher areas in the city with the water from this aqueduct.

The failure of the Hadrianic aqueduct required it to be repaired as soon as possible after the earthquake, and the enormous time pressure is clearly visible in the different quality of the masonry. While the Hadrianic aqueduct was built with very careful masonry, where even an aesthetic element can be observed in this functional building, the Antonine aqueduct was often very poorly built with irregular quarry stone layers and levelling courses. The stone material was quarried immediately above the route, so the material was also used immediately in place.

In the first and the last sections, the aqueduct lies underground, only the bridges are still visible here in surface construction. In these areas there are also four tunnels built in a Qanat system, whose documentation and exploration was undertaken by a team of archaeospeleogists of the group of Sotterranei di Roma. Exploratory excavations, at important points, yielded valuable information. The salvage excavations in the urban area of Kuşadası, which began only after the completion of our project, showed that the underground conduit is still almost entirely preserved and it also confirmed our previous assumption that the Hadrianic conduit was already constructed with a larger, vaulted cross-section for better maintenance in the underground area.

This contribution shows that only with the cooperation of many specialists in an international and interdisciplinary team that so many new results could be achieved and such a long and complicated structure could be investigated to the smallest detail.

Water in Istanbul. Rising to the Challenge, an interim report on the first year

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The principal aim of our project is to increase understanding of how ruling authorities, engineers and urban planners have attempted to respond to the significant water management challenges facing Istanbul at two key periods in the city's life - the transition from Byzantine to Ottoman rule and the period of massive population explosion beginning circa 1980 - and then to use this new knowledge to inform discussions of contemporary problems and the development of future solutions.

Interdisciplinary collaboration between archaeologists, historians and engineers enables the application of present-day hydraulic engineering modelling methods to data from the Byzantine and early Ottoman period with the aim of generating new knowledge and understanding of how the past system functioned and was managed with special reference to the city's First Hill, the Topkapı Saray.

The research programme is cross-referenced with the design considerations of the modern infrastructure and is incorporated in a participatory knowledge generation process engaging academics from UK and Turkish higher education and research institutes as well as those responsible for the city's current water management infrastructure, including professionals from Istanbul Water and Sewerage Administration (ISKI) and local lay stakeholder bodies including the Istanbul Metropolitan Municipality and Istanbul Planning Agency.

The mega-city of Istanbul, spanning two continents, is today the largest city in Europe. Since its foundation as a capital in 330, and despite the benefits of situation and setting, Constantine's legacy was to found a new city 'thirsting for water', to quote a 4th century orator. Only the provision of the ancient world's longest water supply line was able to meet the increasing demands of a growing city. However, the problem was not easily resolved and over later centuries there was a continuing challenge, which became particularly significant at key moments of change and transformation.

Critical environmental, political or economic events can challenge the sustainability of complex infrastructure systems. Radical regime change, as in 1453 when the Ottomans conquered the city, raises important questions of concerning the continuity of water-related infrastructural systems and how they were modified and replaced.

A major objective of this project is to develop a better understanding of the Ottoman water management system in the Topkapi area, Constantinople's First Hill and the Acropolis of Byzantium. Here functional changes made large infrastructural remodelling necessary and there were particular problems presented by the relative elevation of the new palace. Targeted archaeological fieldwork and historical research, in part based on previous studies by our colleague Dr Cigdem Ozkan Aygun of ITU, as well as collation of existing material, provides data for extensive GIS mapping of the water management system in the Topkapi area, and for investigation of its functionality using hydraulic modelling. Our paper will report on the first year of research of the British Academy funded project, the results and interpretation of GPR survey in the vicinity of the palace, the development of a GIS integrating all previous map and hydrological data and the challenges faced by the implementation of hydraulic modelling.

From the parts to the whole: modelling the water supply system of the eastern Caelian through an integrated approach to hydraulic structures

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The Caelian is an elongated hill located in the southeast area of Rome. Over the centuries it went through several transformations, changing from a quasi-rural space on the edge of the city to a monumentalised centre of exceptional importance.

Between the Mid Republican age and the late 1st century AD, five aqueducts were built across the hill: the *Aqua Appia*, *Aqua Marcia*, *Rivus Herculaneus* (a subterranean branch of the *Aqua Marcia*), *Aqua Julia* and *Aqua Claudia* (*Arcus Neroniani* branch). Even though archaeological evidence for some of these no longer survives, all played a vital role in supplying the region's growing population. The Caelian's water distribution system was probably locally managed, but it was connected to large-scale infrastructure, being an integral part of the complex and extended urban hydrological network.

The aim of this research project is to identify which aqueducts supplied the Caelian, what volumes of water were transported at different periods, what kind of structures were planned along the aqueducts' courses to facilitate the local distribution, where these structures were located, and how the general distribution system worked.

As a part of the Rome Transformed project, a five-year project intending to investigate the transformations of the eastern Caelian from the 1st to the 8th century AD, interdisciplinary collaboration is at the heart of this research. The project benefits from an integrated approach strategy by channeling all the analytical data into a 3D GIS environment, which will serve as the basis for interpretation, helping to address lacuna in the data, and support the creation of *provocations*: 3D models which will help visualize the key developmental phases of the urban landscape of the quarter over time.

The methodology advanced here brings together several different elements, such as a detailed survey, the identification and cataloguing of all hydraulic features attested in the area, structural analysis, study of legacy data and literary sources, physical geography, geophysical analysis, chemical analysis of water deposits, hydraulic mortars and soil sediment, and water flow modelling. These datasets will provide the base where integrate the water net reconstruction hypothesis, considering what hydraulic features had to be necessary for the correct functioning of the water system. The final output will be an advanced 3D visualization of the Caelian supply system and distribution.

As this research is still in progress, this contribution will report on work in progress, offer some preliminary results and open discussion, seeking to advance integrated study of the Caelian water system.

Subterranean surveying methods insights in light of the new survey of the Biar Aqueduct, Jerusalem

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Jerusalem has always suffered from a problem of water supply, due to its topographic elevation and the scarcity of stable water sources in its immediate surroundings. During Classical Periods, this issue was solved by a dense and long water system, comprised of four separate aqueducts, having total length of c. 80 KM.

The Biar aqueduct is the most sophisticated of the four, including the Biar spring, an underground Shaft Tunnel ~3 km long harvesting groundwater (cuniculus), a dam, a surface channel, and a tunnel traversing a ridge. Due to its location far from modern urban areas, in an agricultural environment, and the fact most of it is subterranean- it is mostly preserved.

The lecture will describe the new survey of the Biar underground Shaft Tunnel, which mapped all of its accessible parts (~1250 m), using designated equipment of speleology world- Disto-X and topodroid software.

Data accumulated from this survey facilitated a new understanding of the cutting-edge hydrogeologic and engineering skills used for this project. Projection of the underground tunnel to the surface, using GIS, enabled tracing the specific ingenious route chosen by the aqueduct engineers and detect intentional and unintentional deviations in hewing process. Discharge measurements taken along the tunnel allowed an estimate of the relative contribution per meter of different segments.

The most significant discovery of this research was the first documentation of the impressive, subterranean, ashlar built segment, which used sophisticated construction methods. This segment (~536m long) is located near the outlet of the Shaft Tunnel and is divided to three sections designed to withstand different loads: (a) in a mechanically weak bedrock, a channel with arched gables and barrel vault specus was built within a hewn winding tunnel, (b) when dug as an open shallow trench, a channel roofed with complex gables of ashlars with drafted margins was built, and (c) to release hydraulic pressure, a channel roofed with alternations of barrel vaults and simple gables set perpendicular to the course of the tunnel was constructed.

^{14}C dating of charcoal embedded in plaster fragments that were sampled from the shafts leading to the tunnel, suggests the Biar aqueduct was built in the mid-first century CE and renovated in the days of Aelia Capitolina in the second century CE. To date, no parallels have been found to most of the construction methods that have been documented in the tunnel, although it is clear the aqueduct builders were guided by imperial knowledge and roman building standards.

Travertine roughness and changing flow conditions in Roman aqueducts

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Travertine (calcium carbonate or limestone) deposits are a relatively undisturbed archive of the ancient flows in Roman aqueducts. Aqueduct water, typically sourced at springs or sometimes at rivers or lakes, often chemically deposited travertine on floors, walls and even roofs of aqueduct channels, due to its richness in calcium and carbon dioxide. Successive layers were laid down one on top of the other, creating a stratigraphy of travertine layering.

Our previous research has already found that, from the geometry of travertine deposits in aqueducts, the actual flow rate in the aqueduct and possibly its variation in space along the aqueduct can be estimated. Also, from the ripples (wave-like patterns) visible in the travertine depositional surfaces the flow rate variation in time (i.e., the water supplied by the aqueduct) can also be inferred.

We present here the analysis of the depositional top surface of several travertine deposit samples found at multiple locations along the channel floor and walls in the Anio Novus and Aqua Claudia aqueducts. These two aqueducts were completed in 52 CE and then maintained for centuries. They supplied many different parts of Rome.

The analysis is conducted using high-resolution scans obtained with a digital microscope and computer post-processing, to characterise the surface into two forms of roughness, corresponding to wave-like formation of larger-scale amplitudes ("macro" roughness) and travertine material roughness of lower-scale amplitudes ("micro" roughness). The latter can be related to the so-called "hydraulic roughness height."

Characterizing quantitatively the travertine roughness is important to evaluate in time the hydraulic performance of large-scale systems such as the ancient Roman aqueducts. Besides physically obstructing flows, the progressive formation of travertine deposits caused an increase of the friction resistance exerted on the flow by the aqueduct floor and walls, compared to the original mortar lining, due to both travertine "macro" roughness (order of magnitude of 100s microns, millimetres, or greater) and "micro" roughness (order of magnitude of 10s microns). This generally led to a reduction of the original "design" carrying capacity of the aqueducts, because the greater the surface roughness of travertine, the lower the flow rates that could be carried within the aqueduct. Moreover, the turbulence created by this roughness could also increase travertine deposition, consequently increasing the maintenance required to remove it. Roman engineers seem to have been aware of both these facts, as they went to great lengths to produce smooth mortar surfaces lining the inside of the channel.

We also discuss how sampling travertine in aqueducts can provide qualitative and quantitative information about their ancient flows, and what geometric characteristics need to be measured to this end.

Geometric and hydraulic analysis of Rome’s Aqua Claudia aqueduct

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We present an investigation of geometry and hydraulic performance of the Aqua Claudia, one of the ‘great’ aqueducts of ancient Rome. The Aqua Claudia was completed in 52 CE together with the Anio Novus. The simultaneous building of these two aqueducts was the largest single addition to Rome’s water system. The Aqua Claudia was maintained for a millennium, testifying to its continuing importance to the city despite vast social changes. A branch added to the aqueduct by the emperor Nero carried part of the water from the Aqua Claudia across the Caelian hill to supply the Palatine hill, the seat of imperial power in Rome.

Geometric data for the aqueduct channel (cross-section width and height, longitudinal slope), comprising 94 points along almost 70 km of the aqueduct, are used to estimate its maximum carrying capacity, that is, the maximum flow rate that the aqueduct could have potentially carried as flow with a free surface. We also evaluate whether this value of maximum carrying capacity was constant through the aqueduct or instead varied along it, possibly because of water withdrawals or construction constraints. Carrying capacity estimates are then compared with those for the Anio Novus, which was built on top of the Aqua Claudia in the final stretch of the aqueduct route leading to Rome. The waters of the two aqueducts were kept separate, at least partly because of the far superior water quality of the Aqua Claudia (noted by writers in the 1st and 6th centuries CE).

The operational (actual) flow in the Aqua Claudia is also computed, based on measurements on travertine (calcium carbonate) deposits at specific locations, and compared with the operational flow in the Anio Novus. This is used to assess the known practice of water redirection from the Anio Novus to the Aqua Claudia during maintenance periods.

The hydrodynamic characteristics of the flow in the Aqua Claudia, such as its water depths and flow velocities (and longitudinal variation thereof) are also evaluated and used as basis for insights in aqueduct design, operation, and maintenance. Again, those characteristics are compared with those in the Anio Novus previously analysed by the authors.

A general geometric comparison of all four ‘great’ aqueducts of Rome (Aqua Claudia, Anio Vetus, Anio Novus, Aqua Marcia) is also presented, to identify possible chronological trends.

Preliminary results indicate that the estimated maximum carrying capacity of the Aqua Claudia varied significantly along its route, as result of slope and cross section geometry longitudinal variations, and was generally lower than previously estimated by other authors. Also, the Aqua Claudia may have sustained a larger operational flow than the Anio Novus. Comparison of slope and channel width and height for the four ‘Great’ aqueducts of Rome (Anio Vetus, Aqua Marcia, Aqua Claudia and Anio Novus in chronological order) generally shows the adoption of a more favourable, overdesigned, geometry over time, with the likely goal of increasing capacity and reducing the need for maintenance.

A computational hydraulic analysis of the aqueduct supplying Great Chesters Roman fort on Hadrian’s Wall

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Great Chesters Roman fort is one of the 17 larger forts situated along the southern side of Hadrian’s Wall and was one of the final forts completed around 128 CE. It served as a stationary camp for several cohorts of the Roman military who served on the wall until its abandonment for the Antonine Wall in AD 138.

Unusually for Hadrian’s wall, Great Chesters was supplied by an aqueduct running 9.5 km from a source at Saughy Rigg washpool and describing a circuitous route, following the contours. This study was conducted to determine the possible flow that the aqueduct might have delivered to the fort in the light of the possible water needs of the people living there.

Ordnance Survey England 1 m Digital Elevation Model data was imported into the ArcGIS software and used to identify the catchments that could have fed water by gravity into the aqueduct channel. The route of the channel remains observable and is recorded on modern maps, suggesting that the modern contours are a good proxy for the land in Roman times. The catchment area identified was 2.303 km^2.

The GIS model was imported into the hydrological modelling software HEC-HMS for the modelling of rainfall runoff. In the absence of Roman rainfall data, publicly available data for the period December 2000 to December 2001 was used, along with corresponding evapotranspiration data. In HEC-HMS, standard techniques were used to model canopy and surface storage and losses due to infiltration. A Clark Unit Hydrograph was used in conjunction with US Soil Conservation Service curve numbers to transform rainfall into runoff to the aqueduct channel, in which it was routed using the Muskingum-Cunge approach. The channel dimensions, after Mackay (1990), were assumed to be width 0.56 m, depth 0.28 m and with a Manning’s roughness (n) value, corresponding to a smooth clay-sided channel, of 0.018.

During the 366 day period simulated, 911 mm of precipitation fell, producing an average discharge of 2.05×10^6 litres per day in the aqueduct, allowing for its maximum capacity. An estimate of the total water demand of people and animals was made as 67 220 litres/day, which is well below the capacity of the aqueduct, though there were dry periods in the summer when the daily demand could not have been met without storage. Whilst no historical rainfall data was available, Büntgen et al. (2011) present a tree-ring based analysis that suggests that rainfall in the 128-129 CE period was consistent with modern times.

Further work is planned to test the sensitivity of our analysis to the values of various parameters in the rainfall-runoff models and to use rainfall data ‘backdated’ using Macrophysical Climate Modelling.

Stories of Roman aqueducts about smart adaptations to natural processes and socio-economical needs

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Ancient large-scale water systems have been studied in detail from textural sources and archaeological remains. Therefore, scientists today are looking for new data sources to retrieve unknowns on water management. Thanks to new scientific advances, modern achieves are now in use. For instance, geologists have introduced calcium carbonate deposits, namely "Kalksinter", in water systems as a new archive to investigate ancient water management, the history of the use of the systems, and adaptation attempts such as restructuring and maintenance. These deposits from the Roman aqueducts, as a new archive, could also provide significant information on ancient climate and socio-economical development. We provide three examples:

A 246km long aqueduct was built in the 4th century to supply *Constantinople*. However, increasing population growth forced Roman engineers to find new sources and the aqueduct was expanded in the 5th century by addition of a 180km long channel from springs to the NW. These adaptations made this structure, known as the aqueduct of Valens, the "longest aqueduct of the ancient world". An enigmatic structural element of the Valens aqueduct, a double section with two parallel channels and two-story bridges can be explained by the need for cleaning the channel, without interrupting the water supply. Other evidence for possibly regular cleaning of this long aqueduct is the presence of only 27 years of carbonate deposits in a channel that worked for at least 700 years. These curiously clay rich carbonate deposits may indicate that the giant cisterns in Constantinople which served the city during dry spells, probably also served to settle clay from the channel.

The first industrial complex of the ancient world, the Barbegal watermills in southern France also provide an example of adjustments made to separate two water sources. Two branches of a city aqueduct of *Arelate* (Arles) were separated to create a longer city aqueduct, and a branch serving the mills for grinding flour. Another enigmatic architectural element, here of parallel bridges, can be explained by the completely different needs of the city of *Arelate* and the mills. The city water structures and the existence of the industrial complex of Barbegal testify to significant socio-economic developments of southern Gaul and its contribution to the Roman economy and technological development.

Besides structural adaptations, aqueduct maintenance in the form of cleaning of carbonate incrustations can be observed in the water systems of *Constantinople* and *Arelate*. However, the most spectacular and visible example of cleaning comes from the *Divona* (Cahors) aqueduct, where such traces were captured as tool marks in the carbonate stratigraphy.

One of the rare examples of a river-fed aqueduct, the water system of *Divona* displays abundant foreign inclusions in its carbonate deposits. Many of these inclusion levels are associated with at least 11 cleaning episodes in a period of 70 years during the last phase of water supply to *Divona*.

Ever since we are dealing with aqueduct carbonate deposits, we have seen examples of how an ancient society created solutions in an attempt to adapt to natural processes and changing urban needs.

Really convincing fantasies? Modelling large-scale irrigated landscapes (as) in the making and why that matters

Maurits W. Ertsen (Delft University of Technology, The Netherlands)

In this contribution, I make an attempt to relate the conceptual notion that everything that we study is "in the making" to the methodological implications of that same notion – especially on studying large-scale hydraulic systems.

The close (perceived) relation between (urban) elites and water control has led to water becoming a topic under rather over-arching models such as the "archaeology of power" (with the model of hydraulic civilizations a most famous attempt (Wittfogel 1957). Without suggesting that Wittfogel provided a convincing analysis, linking water and power still makes sense – and this is what we do in my group through agent-based and hydraulic models. We argue that engagements between human and material agents in our models are key to understand how water systems shape and transform 'relations of power'. In emerging relations, technologies, artefacts, and the material in general 'help to shape what counts as "real" ' (Verbeek 2006 , 366). Negotiating the meaning of matter/nature has at least two dimensions: 1) negotiations between humans and non-humans co-shaped power relations in ancient practice and 2) we in the present chose how to represent (ancient) practice, including conceptualizations of the "material". Our reconstructions should offer the same 'possibility of holding society together as a durable whole' (Latour 1991, 103) as the constructions did for ancient water users.

My group aims to clarify how the actor-network of power in the making was shaped by human and non-human agents alike. Power needs to produce its own support. This conceptual notion has direct implications for the methodology to study ancient hydraulic systems – in our case irrigated landscapes. We use two types of models: hydraulic and agent-based models. Hydraulic models allow us to reconstruct scenarios for use and extension – allowing us to argue that certain scenarios reflect the archaeological record (see for example Zhu et al 2018). We use ABMs to study the processes of change themselves, as these models allow inclusion of decision making. As much as our hydraulic models help the ABM to have more agent-based water flows, we aim to bring human interaction in the hydraulic model, using specific modules to be programmed – as is done now for traditional control studies in water systems.

I would argue in general that to understand ancient hydraulic systems one needs proper water behavior. As such, my methodological answer to the challenge set in this workshop is to develop hydraulic models with ABM properties. In social practices, human agents continuously link themselves with other human and non-human agents. Our model-based, action oriented methodology proposes to replace the bird's eye view on social and physical processes at a lumped scale with an approach that takes the many different perspectives of agents as the basis for modelling. Our approach has the added benefit that it offers the same type of agency to (Roman) agents as we allow ourselves in our own time: not too much perhaps, but certainly not just predefined by our successors (Ertsen 2021).

Public hydraulic infrastructures at Roman's cities *ager* in central Italy: dams and dykes

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The operating capacity of many of the buildings which were part of the monumental architectonic programme in Roman cities, and quite specifically, those closely linked to water, had a direct reflect in the territory of those *urbs*: colossal public infrastructure works which were, at the same time, almost invisibles because, in many cases, they were not monumental buildings. However, such extra *moenia* activities were, in fact, part of the materiality of the Roman rule further on the city. It also testifies a deep territory knowledge, which made possible a strong control, use and exploitation of water resources.

Starting from these general assumptions, I have developed a research project focused on Roman hydraulic architectures –intended to retain and/or divert the waters (dams, diversion dams and protection dykes)- in central Italy. Such constructions are rarely specifically analyzed and, in fact, it doesn't exist / it lacks a catalogue of them. This first classification is an obligatory step prior deepening on these infrastructures research, which will allow creating a database for further scientific studies.

The project is developed using multiple approaches, tested throughout various previous interdisciplinary projects (with civil engineers, geologists, archaeologist and architects).

The theoretical frame and methodological procedure consider both the architectonical parametric of the works and its unbreakable ties to the territory with its diachronical alterations. Those two different approaches permit to draw parallels between constructive works, delve into its temporary evolution, and the articulation of a new contextualized historical discourse.

Part of the Project will be a scientific colloquium (*Dighe, argini e sbarramenti: il dominio e la gestione delle acque nell'italia romana*) which will take place at Rome in October 2022, under the chairmanship of Dir. Antonio Pizzo and Marisa Barahona. The project main goal will be to generate a first corpus of Roman dams in Italy, deepening on three topics: a) building and process of works; b) dams as part of organization and management of the territory; c) sources, destination and uses of the reservoir water.

The proposal submitted to the *colloquium* intends expounding the project theoretical and methodological basis, presenting the results achieved.

The Thermal Baths Archaeological Park of Baiae and the *Aqua Augusta* Story: an attempt of reconstruction

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The Thermal Baths Archaeological Park of Baiae (Bacoli - Naples), is a large site sits in a very dramatic location. Lying on the slop of a hill named Sella di Baia, huge buildings, facing the *Lacus Baianus* and overlooking the Bay of *Puteoli* and Mount Vesuvius far away, were located, from the top to the bottom, on terraces decorated with pillars, porches, gardens and many water fountains.

Here, in this luxury place, for almost five centuries (end II-I BC – IV AD), the roman aristocrats spent their relaxing holidays in the renowned *otium* of the *pusilla Roma*, as Baiae was called for its beauty ad for the numerous royal properties.

Several large domes were raised including bathing systems and many underground structures: water tanks, volcanic steam ducts, hydraulic features are present at the site. Their transformations over time is an interesting guideline to better understand the use and the destiny of the main water supply of Campania: the famous Aqua Augusta, the Serino aqueduct. Its construction is dated to the I a.C., by the Emperor Augustus for the Royal Navy, from the Serino springs to the large *Piscina Mirabilis* at Misenum, not so far from Baiae.

The modifications suffered by the differents ectors of the Park are important not only to surface the building phases but also to have a clearer idea of what happened to the aqueduct in the years. Infact, there are many parts of the aqueduct running through the hillside, behind the villas walled up on the volcanic and soft yellow tuffstone: a portion cut by the road, just outside the limits of the Park; another one above the ticket office; a portion behind the so-called *Ambulatio* Villa; another one above the so-called Piccole Terme, including a large chamber of control. Furthermore, drainpipes, water tanks with large layers of limestone, wells and rooms turned into cisterns.

We would also attempt a reconstruction of the Aqua Augusta building story between the Lucrino Lake and the *Lacus Baianus* and, according to the findings, old and new, try to understand if it was going *per montes* or built on arches or both: from the Lucrino gallery to the underwater findings; from the Averno Lake to Cuma (beside the Cocceio’s Gallery); from the Fondi di Baia evidences to the Castle and the findingsat Cappella (Misenum).

The *Aqua Alsietina* between urban and extra-urban context

Maria Grazia Cinti (Independent researcher)

The *Aqua Alsietina*, also known as ‘*Aqua Augusta’* is one of the most unknown aqueducts of ancient Rome but today it is better known thanks to my PhD results.

In the almost 4 years of research, in fact, I studied all the literary sources (not only the ancient but also the modern ones) and the documents but what really helped was the intensive survey conducted between the *incile* and the terminal point.

The water for this aqueduct was kept in the Lake of Martignano (ancient *Lacus Alsietinus*), 30 km far from Rome, at a height of 207 meters a.s.l. This lake is close to the Lake of Braccianus (ancient *Lacus Sabatinus*), where there were the springs of the *Aqua Traiana*. The Alsietina was long 22172 paces but only 358 were above ground, so it have always been very difficult to find archaeological remains belonging to this aqueduct.

The Alsietina, like all the other roman aqueducts, had it course for the larger part outside the city, and today, thanks also to the aerophoto-interpretation, several artifacts connected to it can be identified. This, unfortunately, changes once we try to find traces of the aqueduct inside Rome because the intense activity of construction erased most of the ancient archaeological remains. One of the peculiarities of this aqueduct appears to be the different building technique: in some areas, in fact, the aqueduct was “cappuccina” covered while in others the *specus* was barrel vaulted. In the Gianicolo hill, for example, in the last meters of the aqueduct’s course (so inside Rome), during the last century some traces of the Alsietina covered by a barrel vault were found under the modern Viale XXX Aprile; on the other hand, along Via Casal Selce (many miles off Rome’s walls), two *lumina* and several other discoveries have been carried out but in this case the roof of the specus was covered “a cappuccina”. So: could there be a difference between the peculiarities of the aqueduct inside and outside Rome? Or maybe this distinction could be the result of some kind of restoration? As it is well known, the Alsietina and the Traiana aqueducts can be strictly connected because Emperor Trajan restored some points of the Alsietina and because thanks to Frontinus we know the existence of a branch of the Alsietina coming from the Lake of Braccianus.

The aim of this paper is to give an overview of the recent studies about the Alsietina and to try to understand if its differences can be traced to the different urban and extra-urban context.

Aspects of the Water Distribution of Ancient Rome

Paul Kessener (Independent researcher)

The city water distribution of Pompeii was realized by means of secondary *castella* (i.c. lead containers) on top of its well-known water towers, connected to the main *castellum* at the Porta Vesuvio and supplying among others the public fountains (*lacus*). In Rome every aqueduct - or its branch - ended at a *castellum princeps,* but in which way the distribution of the waters was accomplished has not been attested by archaeological remains: virtually nothing has survived of the fixtures that were installed in these *castella*. But numerous finds in Rome of (stamped) *fistulae* indicate that pipeline systems were commonplace. In *de Aquaeductu Urbis Romae* Frontinus mentions the secondary *castella* for each aqueduct of his time, a total of 247, that together delivered 9687 *quinariae*. For public use there were 591 *laci*, Frontinus writes, taking 1333 *quinariae.* How Rome's secondary *castella* serving these *laci* looked like remains uncertain as no (Pompeiian type) water towers have been found. However, we may have some indication. Near the Porta Viminalis a round structure survives, described by Lanciani as '*una specie di torrino, o pozzo circolare*'. Investigation revealed that the upper section of the tower was equipped with a water tank and served as a transfer station for large-sized lead conduits.

Built on its seven hills, most of Rome's aqueducts came in at a level sufficiently high to service some of the hills, the Aqua Claudia and Aqua Anio Novus were high enough for all. A direct connection of *fistulae* through the wall of the channel would be a possibility as is attested e.g. for the aqueduct of Aquincum (where also remains of water towers equipped with ceramic pipes have been found). If the Arcus Neroniani on the Caelian hill, branching off from the Aqua Claudia, was equipped with such off-take pipes, the question remains whether these pipes led to secondary *castella* (in buildings?) preserving water pressure for further distribution, as was much later common practice in the 19th century CE and before.

An integrated hydraulic model for ancient Pompeii: simulating the water distribution network

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The ancient Roman city of Pompeii is known for the good state of preservation of its various water structures. Its original urban water distribution system included an external aqueduct channel and receiving tank (*castellum*), at least 15 water towers and 40 visible public fountains, more than six public cisterns and reservoirs and over 100 connections to private buildings, including private reservoirs and garden installations supplied by pressure piping. There is no certainty of the exact dating of the different structures, although scholars have postulated that all were in operation in the Augustan age, with various authors providing hypothesis on the possible layouts of the water distribution network.

Recent work at Northumbria has resulted in a quantitative understanding of the water flow through the public *lacus* fountains (Monteleone et al., 2021) and has given insights into the various diameters, lengths and arrangement of the lead pipeline that could have supported this (Monteleone et al., Under review). We now present the preliminary results of a computational model of the Pompeii water distribution network, with particular focus on the public fountains. The modelling approach employed is typical of modern hydraulic engineering simulations of pressurized water supply networks. Results are validated by comparing the flows at the fountains with our previous estimates obtained with simplified hydraulic hand calculations.

The data for this study came from a variety of sources, such as previous studies, surveys by the authors of this paper carried out in the past four years, digital cartography provided by SIAV-*Pompeii Beni Culturali.* The data were compiled in a GIS environment using QGIS and then exported into the hydraulic modelling software EPANET to run the numerical simulations of pressurized flow in the water distribution pipes. The model includes the *castellum*, all the known water towers and the pipes supplying all the known the public fountains. To account for the uncertainty associated with some of the data in the geometric dataset, sensitivity analyses were carried out to model the effect of the variation of the input parameters within reasonable ranges.

This study can potentially identify the most likely among the previously suggested layouts for the water distribution network in ancient Pompeii and can quantitatively evaluate the supply needed from the external aqueduct under various operational conditions.

Following completion of this work, it is intended to incorporate further model elements describing water use in private buildings, waste water and rain water runoff into a fully integrated numerical computer model.

Aqua Traiana. Reuse, restoration and maintenance aimed at productive functions and urban development from Middle Ages to 19th century

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The Trajan Aqueduct represents an exception among the ancient hydraulic infrastructures, maintaining full functionality from the ancient age to today.

It was built in 109 AD by emperor Trajan to supply the Transtiberim and after a route of over 57 km from the lake Bracciano to Rome it entered the city on the Janiculum Hill.

After the cut made by the Goths in the 6th century, the aqueduct was reactivated to supply the Vatican and to power the watermills.

After a new period of abandonment, the full functionality of the conduit was restored by Pope Paul V in 1612, with the primary purpose of providing motive power to the factories and bringing water to the fountains at S. Pietro.

The interventions of the pontifical engineers are particularly evident in the elevated sections and in the large chambers for water distribution (‘botti’), while the underground conducts and the uptake structures are still the original ones from the Roman age.

One building, many purposes. Assessing transformations in water provision, management, and distribution in the baptistery of St. John Lateran in Rome

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The baptistery of St. John Lateran in Rome is known for being the oldest monumental baptistery of Christianity, built during the reign of the emperor Constantine in the first half of the 4th century AD to the west of the Basilica of the Saviour, the world's earliest Cathedral. Despite the relevance the building gained after its construction as the model for many monumental baptisteries of western Christianity, the baptistery was not erected ex novo, as a self-standing monument over the dismantling and levelling of pre-existing buildings. Rather, it is the result of a complex process of reuse, adaptation, and transformation of the structures of the Severan and late 3rd century bath complex that preceded it.

Our paper looks at the structural transformations of the complex and seeks to understand how far the need to make the most of the pre-existing thermal and hydraulic infrastructure, in their successive transformations, affected the design of the Christian building.

Hydraulic systems, reuse and transformations: from the *Aqua Claudia* to the Felice Aqueduct

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A remarkable example of the reuse and transformation of a large hydraulic system is represented by the Felice Aqueduct. It reused the springs that fed the ancient Aqua Alexandrina, and reused the supporting structures of the Aqua Marcia and Aqua Claudia: therefore it represents an extraordinary example of 'continuity of the antique'. The functionality itself of the aqueduct continued over time up to the present day. In fact, the original channel of the Felice Aqueduct was used until the Eighties of the twentieth century. In particular, the paper presented here focuses attention on a specific stretch of the aqueduct, about one kilometre long (0,6 miles), located between Via Tuscolana and Via del Mandrione. It is now included in a large area owned by the Bank of Italy, which has guaranteed its protection over time and still guarantees better accessibility and fruition.

The progressive acquisition of the surrounding areas by the Bank of Italy has in fact prevented the Aqua Claudia and Felice aqueducts from being engulfed by the disorderly urban development, which negatively characterizes the rest of the route, in particular between the Aurelian Walls and the Via del Quadraro. Their arches, in fact, still run isolated in the green as in the times of Goethe and Stendhal. The significant restoration work carried out in the Nineties of the twentieth century also brought to the surface a long stretch of the ancient aqueducts service road. It fully preserves the paving of the driveway and the sidewalks (*crepidines*) for pedestrian transit.

In the analysed stretch, the *Aqua Claudia* presents all the complex masonry stratigraphy that characterizes it, due to the superimposition of the restoration interventions, carried out in ancient times on the original structure of the first century. On the pillars, the arches and the *specus*, made entirely of *opus quadratum* of tufa and peperino (the second material was used in the points of major structural loads), the brick sub-arches of the Hadrian age and the rebasing (also in brick) of the Severian age are overlapped. In addition, a further re-wrapping from the age of Honorius is visible, partly in brick and partly in *opus listatum*.

The Felice Aqueduct is part of this complex infrastructural system, reusing the pre-existing *Aqua Claudia* in two ways: where its elevation was completely lost, it reused the collapsed building material, incorporating it into the cement work of the sixteenth-century aqueduct; where the elevated structures were preserved, for long stretches up to the *specus*, a complex work of adaptation was instead necessary. As the Felice channel is much lower than the one of *Aqua Claudia*, in fact, it was necessary at the same time to infill the arches and drill the pillars of the pre-existing aqueduct. This intervention allowed a considerable saving of material and labour, as well as time and costs, but at the same time, it caused a structural weakening of the ancient walls, with a shift of the loads towards the outside, which made necessary the substantial restoration works held in the 1990s. Further interventions for the next future are already being studied by the Capitoline Superintendency for Cultural Heritage of Rome (Soprintendenza Capitolina ai Beni Culturali) and by the Bank of Italy.

Aqua Claudia in the archaeological area of Santa Croce in Jerusalem: characteristics of the aqueduct, the secondary water distribution structures and the restoration works

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The archaeological excavations supervised by the S*oprintendenza Speciale Archeologia, Belle Arti e Paesaggio* of Rome, along the final stretch of the *Aqua Claudia* at Porta Maggiore, have furthered our knowledge of this aqueduct and the various modifications that it underwent over the centuries, and of several secondary hydraulic structures in the Archaeological Area of Santa Croce in Gerusalemme. A series of excavations, together with a structural analysis of the building interventions alongside the southern flank of the aqueduct, were carried out from 2017 to 2021, which have clarified the nature of the changes made to the site over time.

The first of these excavations brought to light an entire sector of the "*domus* of portraits" and a supporting pillar of the *Aqua Claudia*, which was reduced in height, presumably at the same time as the destruction of the contiguous housing complex under the emperor Honorius, who had this stretch of the Aurelian Walls reconstructed. This pillar was originally built with blocks of so-called "*lionato*" tuff, joined together by dovetailed bronze clamps, and the excavations clarified its relation to the abutting structures dating to a later period. The aqueduct was transformed into a single masonry façade, with its arches closed by solid walls, leaving only a few openings giving access to the northern side of the wall.

To the east of the *domus,* modern masonry additions to the *castellum aquae* were removed, in the context of the continuation of a previous excavation, led by V. Santa Maria Scrinari in the late 1950s. This intervention revealed a series of overlapping basins, built at various different historical periods, connected to a collection basin below the level of the *castellum aquae*, and then to a smaller aqueduct, which provided the surrounding area with water. Raised upon low arches, made of *opus reticulatum*, it carried the waters of the *Aqua Claudia* to the north-west.

Two terracotta pipes were found entering the *specus* of this smaller aqueduct, although these had been covered up following extensive restorations in the 1970s. They were probably connected to lead piping leading to masonry basins nearby, one of which can be identified as the fragmentary structure that was fed by the easternmost terracotta pipe.

The recent investigations have made it possible to reconstruct the architectural layout and water distribution system of the *castellum aquae* together with the position of the new water distribution tank, located in the upper part of the structure.

In the early Middle Ages, the arch of the *Aqua Claudia* behind the *castellum aquae* partially collapsed and was restored by a wall that closes the arch, using tuff blocks of irregular shapes and sizes, a technique that is similar to several reconstructed sections of the Aurelian Walls dated to the 8th century. A damaged portion of the *specus* was never properly repaired and reintegrated, but was simply filled up with concrete, probably in the context of the restorations carried out by Pope Adrian I.

***Aqua Publica, Luxuria Privata*: the evolution of the public water system and its impact on Pompeian houses**

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The Pompeian public water system experiences a deep transformation after the introduction of the Serino's aqueduct, during the Age of Augustus. Providing water to all the *Regiones* with a structured water network, the new hydraulic organization defined a macro transformation on the urban structure, like the modernization of many public buildings and the creation of new public services, the most visible of which is the work-site of the Central Baths, ongoing at the moment of the eruption. This proposal will analyse the impact that such changes had on the private context, by focusing on the micro transformations occurred to three Pompeian houses, completely renewed in the structures and in the decorative programme, by the introduction of a *nymphaeum* in their domestic scenario: House of the Anchor (VI 10, 7), House of the Golden Bracelet (VI 17, 42) and House of the Centenary (IX 8, 3.6).

Hydraulic systems in Roman theatres: the transformation of the theatre in Ostia

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Following the recent interest in the study of water system, my Phd research focus in the study of water displays hosted in Roman theatres. It is well-known that Roman amphitheatres could be used for water displays, the arena filled with water to mimic sea-battles or other performances (Coleman 1993). Less considered, however, is the use of theatre buildings for dramatic water spectacles. Gustavo Traversari (1960) was the first to consider this theme closely, hypothesizing a type of performance called the 'tetimimo'; and, more recently, Anne Berlan-Bajard (2006) has extended his work, establishing that such water displays took place well before Late Antiquity. Nonetheless, they remain disputed in nature, lacking proper definition, and, above all, close relation to the archaeological evidence. Recent monographs on theatres (Rossetto and Pisani Sartorio 1994, Sear 2006) lack full consideration of such details, and modern architectural handbooks (Gros 1996) underplay the role of water in Roman dramatic performances. Evidence for the supply of water to theatres remains altogether neglected.

The geographical area of the research is the Mediterranean along which the Roman Empire experimented with a new urban landscape. The identification and recording of hydraulic supplies in these buildings have been done through published works. It has been counted 102 buildings where tracks of the hydraulic system have been observed. What can be said till now it's that in most cases these structures are related to the rainwater sewerage system rather than the use of these buildings for hosting aquatic displays. Nevertheless, the presence of basins in the orchestra area or the evidence of the use of the orchestra as a pool in these spectacle buildings, demonstrate that these performances were played. An example of the later use of the orchestra as a pool (kolymbethra) is the theatre of Ostia, dated in AD 4th century. At this time four radial rooms of the cavea and the axial corridor were converted into reservoirs to store water that was used for filling in the orchestra itself. This is the only example in all the Mediterranean area. Thanks to the study of the original excavation reports and fieldwork on site it has been possible to recreate the plan of the hydraulic system of the theatre. Changes and additions due to the enlargement of the theatre itself were consequently followed by a new hydraulic system to support the upcoming necessities. In this light, the theatre of Ostia is a key study for investigating the changes that occurred in this type of building from the Age of Augustus till Late Antiquity, not only in terms of structural and engineering needs but also cultural demands.