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Constructive Challenges in the Water Supply to Cities, from Roman Times to Modern Times. Some Reflections Based on the Portuguese Reality

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ABSTRACT
Water, as an essential element for life, has always been present in the daily lives of societies. In the case of urban agglomerations, the quantities of water needed to supply them have in some cases been extremely challenging for human abilities, not only in terms of collecting it, but also in terms of transporting it and distributing it for final consumption by the population. Today, the lack of water continues to be a concern, taking centre stage in the global political agenda and in the UN's 2030 Sustainable Development Goals. Convinced that the lessons of history can help minimise the harmful effects of climate change, the aim of this work is to analyse some of the constructive and architectural solutions found by past societies to obtain water, from which we can learn to preserve and value this important resource. Our approach will focus on analysing cases that refer mainly to the urban landscapes of Portuguese territory, as it is a territory that, in addition to having an occupational history that dates back to ancient prehistory, is characterised by a diversity of river basins and a relief that presents a great variety of forms, but which has nevertheless historically faced various challenges related to the supply of water to its urban centres. Likewise, in order to be able to attest to the fact that the lack of water was a common shortage in the overwhelming majority of urban societies in the past, we will chronologically base our approach between Roman times and the Modern Age, necessarily taking into account the different historical and cultural contexts of the examples presented, as well as the water resources they had, which is why we have structured our presentation in three parts. The first is dedicated to water supply requirements in roman cities, the second to the analysis of continuities and ruptures in the supply of water to the medieval city and third to the main challenges facing modern cities in the field of hydraulic construction. Finally, in the concluding remarks we reflect on the different solutions found, but also on the changes that have occurred in construction solutions, their diffusion and/or rehabilitation throughout history.

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1. Introduction

The problems that have arisen in recent decades around the important resource of water, as well as the knowledge accumulated about its management and use in the past, have led to the publication of numerous studies and the organisation of specific scientific meetings on the subject, fuelling and prompting the renewal of research in this field (Porfyriou and Genivese 2012).

In reality, the study of the constructive challenges of water supply posed to past societies currently benefits from a very diverse range of data from different types of information sources, including written, iconographic and cartographic, archaeological and material, but also surviving buildings from different historical periods that are still part of today's landscapes and are part of their cultural heritage.

However, although water catchment sites can be found all over the territory, most of the information is undoubtedly related to urban centres, making it possible to document how societies have related to this resource and to analyse the importance they have attached to it, as well as the way they have managed it, while at the same time making it possible to assess the changes that have taken place throughout history, particularly between Roman and Modern times.

Even so, the study of water supply in cities is a complex research topic, in that each city is a particular case study, taking into account the singularities of each of the respective geographical and historical contexts, and it is extremely important to analyse the topographical and geohydrological framework in which each city is located, as well as the surrounding region, This also requires specific knowledge of the hydraulic engineering techniques that were adapted to the resources of each city at different times in history, as well as the

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infrastructures used to distribute water to the population and to the different spaces and buildings where it was consumed. In this sense, it is also important to consider the social use given to water, which would have contributed significantly to the volume consumed by urban communities.

In the case of Roman cities, archaeological evidence as well as written and literary sources document the importance that this resource assumed in this society. In fact, a large part of the public infrastructure preserved in Roman cities is directly or indirectly related to water, bearing witness to concerns about its regular supply and distribution, its social and cultural use, as well as demonstrating that water management was one of the main challenges in the overall organisation of Roman cities (Adams 1994)

Although Roman technological systems for collecting and managing water continued to be used in some urban centres during the Middle Ages, as some archaeological investigations have shown, the amount of water used decreased significantly from the 5th century onwards with the disappearance of Roman equipment and spaces that were highly demanding of water, such as bathhouses and show buildings, or garden areas. In reality, the greater austerity of social and cultural habits imposed by Christianity and the new political framework that emerged, as well as the shrinking urban population, certainly contributed to a decrease in water consumption in medieval cities and, consequently, in investment in equipment related to its use in urban spaces (Magnusson 2002).

However, from the end of the Middle Ages onwards, problems with the lack of water supply to cities led to significant changes, both in terms of water collection sites and distribution equipment, particularly with the re-entry and spread of aqueducts in the urban world (Trindade 2014) and, from the 16th century onwards, issues related to the supply and management of water resources once again acquired a preponderant role in Modern Age society (Rodrigues and Marín 2020).

Inevitably, analysing the theme of water in the city presupposes considering various aspects of urbanism, including the place where the water was collected, the means and techniques used to collect it and then convey it to fountains, fountains, tanks, public and/or private buildings. This is indeed a very interesting subject due to its complexity and the need to cross-reference different sources of information to analyse the various aspects related to this indispensable element of urban life.

In this way, we will endeavour to value some of the knowledge produced about the constructive challenges surrounding the city's water supply, based on cross-referencing the data provided by different sources of information, from Roman times to the Modern Age.

2. Water supply requirements in roman cities

Supplying water to Roman cities could in many cases be extremely challenging, because although rainwater was an important source of supply, it was not sufficient for the levels of consumption that the cities required, which is why water was mostly collected from natural sources that ran underground or deep underground or through dams and reservoirs (*saepti*) and then conveyed via aqueducts to the urban centres (Adams 1994, 488)

The practice of collection rainwater is well documented in all excavated Roman cities, as the Roman did so through the tanks found in practically all the open spaces inside Roman houses (*domus*), usually located in the peristyles (peristylum) and atriums (*atrium*).

The best examples of this type of tank can be found in the atriums of the domus of the Italian cities of Pompeii, Herculaneum and Ostia, thanks to their particular preservation, although the great variability of these structures is well attested to by the countless structures excavated in recent decades (Koloski-Ostrow 2001), particularly in Portugal (Magalhães 2019).

In the atrium, usually in an axial position, the tank, *impluvium*, located next to the pavement, received rainwater that entered from an opening in the roof of the house, the compluvium. These tanks, which varied in size and morphology, were shallow and the water could then be channelled into underground cisterns. The cladding could also be made from different types of materials, such as tesserae or marble, as can be seen in the Tramezzo di Legno house, in Herculaneum, Italy, see Figure 1 (Koloski-Ostrow 2001).

The water collected in this type of reservoir was essentially used later for irrigation and washing. Similarly, the tanks in the gardens, especially in the

Figure 1. House of Tramezzo di Legno, in Herculaneum, Italy.

houses (peristyles), served the same function, although these spaces, the peristyles, were very particular domestic units, associated with the private life of the masters of the house (the *dominus* and the *domina*). In this regard, it is worth mentioning the two private peristyles, both with a tank and garden, found in the House of Cantaber, in Conimbriga (Portugal), namely the large central tank, with curved shapes typical of 2nd century luxury architecture, see Figure 2) (Magalhães 2019).

However, rainwater was not enough to meet all the needs of Roman urban society, which is why groundwater collection was also very common and is represented by wells (*putei*), which have been archaeologically documented in various places throughout the urban areas of many Roman cities (Fortes 2008).

For the Roman city of *Bracara Augusta*, present-day Braga, founded by Emperor Augustus between 16/15 BC in the north-west of the Iberian Peninsula, a total of 11 wells are known so far. The way in which the city of *Bracara Augusta* was organised since its foundation is sufficiently well known, thanks to the results of the urban archaeology project that has been ongoing since 1976 (Martins, Fontes, and Cunha 2013). The foundational urban plan projected a rectangular city, occupying an area of around 30 Ha, structured in orthogonal streets and square blocks, with around 156 feet on a side between the axis of the streets, which included streets and porches of 12 feet and built areas of 1 actus (120 feet). The site where *Bracara Augusta* was built benefited from a rich, relatively shallow groundwater table, which may have favoured the collection of underground water. The wells documented so far had similar characteristics and chronologies, integrated into houses and craft establishments, as is the case with the well that existed in a glass-making craft complex, set

Figure 3. Roman well (Casa do Poço, Braga, Portugal) ©UAUM.

in a flagstone courtyard, see Figure 3. It had an internal diameter of 0.90 metres and its rim was topped by large rectangular granite ashlars with a square cross-section that were set high up. Another example is the well discovered in the Carvalheiras domus, with the same internal diameter as the previous one, 0.90 metres, having been excavated to a depth of 3.8 metres, which made it possible to observe its wall executed in careful parallel horizontal courses of granite blocks (*opus vittatum*), see Figure 4 (Martins and Ribeiro 2012).

The city of *Bracara Augusta* also has a water fountain, one of the few to be found in the Roman cities of the Iberian Peninsula. Known as Fonte do Ídolo (Fountain of Idol), it is a sanctuary/fountain carved

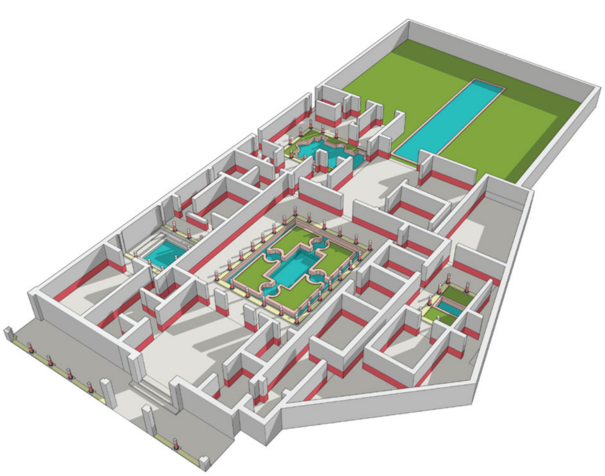

Figure 2. House of Cantaber, in Conimbriga, Portugal, ©FM (Magalhães 2019, 380).

Figure 4. Roman well (Domus das Carvalheiras, Braga, Portugal) ©UAUM.

into the rock of indigenous origin, dedicated to the goddess Nabia, a deity associated with water, but also with fertility and nature. Located in a peripheral urban area, this fountain/sanctuary was the subject of a monumental process dating back to the early days of the city's occupation, marked by sculptures and inscriptions that were surrounded by a granite masonry wall. The fountain's water came from a spring and its provenance was probably significant, given that in Flavian times the monument underwent a small remodelling process that included the construction of a tank. Its water probably supplied an associated bathing complex, identified on the south side of the fountain, see Figure 5 (Garrido Elena, Mar, and Martins 2008).

However, in general terms, the aforementioned collection systems did not guarantee the quantity, regularity and quality of water needed, so in the vast majority of Roman cities water had to be collected on the urban periphery and brought into the city via aqueducts.

The type of works carried out by the Romans to collect water depended on whether the water was on the surface, as in the case of rivers or springs that flowed to the surface, such as the fountains mentioned above, or whether it was underground, in which case it had to be collected by means of drainage galleries, which collected the water from the auriferous zone and led it to the outlet. From there it was taken to the city using aqueducts.

The term aqueduct comes from the Latin *aquae ductus* or *ductus aquae* and means precisely the conduction of water, which could be underground, above ground and/or or aerial, and since it was a large-scale work, it required significant funding from the *public aerarium*, or sponsored by rich men, by *summa honoraria*. The technical management of the work was delegated to a hydraulic engineer, or an *architectus*, and was the responsibility by the *cura aquarum* (González Tascón 2004).

Although there are several archaeologically documented Roman cities in Portuguese territory, most of their aqueducts are not well known. A circumstance that can be explained by the fact that most provincial Roman aqueducts were not aerial and monumental, but surface and underground. The best known Roman aqueducts in Portugal are those that were reused later, particularly in the modern age, such as the Prata Aqueduct in Évora, an aqueduct with Roman foundations on the remains of which the current 16th century structure was built (Branco, Nunes, and Bandeira 1996). In the case of the Roman Alcabideque Aqueduct, which feeds the city of Conimbriga, a combination of aerial and underground sections is documented, with the last 170 metres running through arches, of which only one has survived (Cravo and Bonifácio 2010).

In fact, Roman aqueducts were therefore complex structures designed to transport water from distant sources to cities, using a combination of gravity and hydraulic engineering. Although most of the Roman aqueducts that supplied provincial cities were surface and underground and followed the contours of the topography of the land, this doesn't mean that they weren't almost always complex and expensive structures that involved a prior study of the region to identify the sources of abstraction in order to guarantee a constant

Figure 5. Fonte do Ídolo, Braga, Portugal (Fountain of Idol) ©UAUM.

supply of good quality water at all times of the year. In fact, this was a premise to be taken into consideration when founding new cities, as Vitruvius points out in Book VIII

So, if the place where the water was collected was high enough in relation to the point of arrival (*cistern*) in the city, it could be conveyed by gravity through conduits, underground or surface like those documented for *Bracara Augusta*, in the Gualtar area. In this case, the structure was built directly into the rock, its walls were made of regular masonry and it was approximately 2 metres high. The internal width was around 0.40 metres and the base was made of rectangular bricks. The whole structure was covered in large, irregularly shaped granite stones (Braga and Pacheco 2013).

However, it was common for there to be topographical accidents between the source and the destination, which would have to be solved with different types of solutions, such as tunnels (*cuniculus*), siphons (*siphon*) and arches (*arcus*) or aqueduct bridges (*pontes-aquae*). In the case of tunnels, which were usually dug into the rock to cross high areas that could not be circumvented, they were lined and there were vertical shafts for ventilation and cleaning. This was a technique used, for example, in the *Acqua Appia* aqueduct, one of Rome's first aqueducts, which made extensive use of underground tunnels (*cuniculus*). In the case of inverted siphons were used to overcome depressions, recommended by Vitruvius as the best way to overcome valleys (VIII, 6.4.6). Similar in shape to a U, they interconnect two chambers, allowing the water that enters one chamber to drop to a lower level and gain pressure, and then return to a higher level. In general terms, the chambers were connected by pipework and the water flowed by gravity through conduits that could be made of lead, ceramic or stone. The inverted siphons technique involved the use of water-pipes, often made by lead (*fistula*), by earth/ceramic (*tubuli*), or by masonry (*canales*), was we can see in Figure 9). Although the former, lead pipes (*fistulae*), were the most widely used for distributing water from aqueducts because they were more resistant to the high hydraulic pressure. These tubes were made of very thick lead plates, joined together and soldered with molten lead. The resulting shape was not perfectly cylindrical, but rather pear-shaped, with the edges of the plate being joined together in an unimproved way (Middleton 1892, 460).

To create a system where water could be led down into a valley and then back up again, using the pressure generated by the difference in height to maintain the flow, the inverted siphons system was made up of three types of elements: 1) downward and upward conduits, which carried the water down one side of the valley and raised it on the other side; 2) water-pipes, made of lead (*fistulae*), designed to withstand the pressure of the siphon; 3) loading and unloading reservoirs, which existed at the beginning and end of the siphon to help regulate the flow and pressure of the water. The inverted siphon technology is well known and it is known that it was widely adopted in the construction of several Roman Hispanic aqueducts, such as the four aqueducts built to supply the city of Lyon (Lugdunum), set up in a region that favoured the use of inverted siphons. Finally, in the case of arcades, aerial aqueducts, also known as aqueduct bridges, built to bridge depressions, the level of the deck had to preserve the horizontal inclination of the conduit, so these bridges were made up of pillars connected by one or more orders of arches, over the last of which the conduit ran, in order to guarantee the stability of the entire structure in the longitudinal direction. For transverse stability, which was more problematic due to the smallness of the cross-section, buttresses were used on the pillars, or cross-sections of the pillars were adopted in order to increase the rigidity of the section in relation to transverse buckling (Fortes 2008).

Even so, the length of the aqueducts varied greatly, depending of course on the distance from the place where the springs were located, with some being only a few kilometres long, others hundreds, and combining various construction solutions, such as arches, inverted siphons and tunnels, circumstances that necessarily made the work more expensive.

In any case, to regulate the quantity and pressure of the water it was necessary to build settling tanks to regulate the quantity and pressure of the water. The quality of the water could be ensured through the construction of drains, or limestone pools, which often existed before the aqueducts entered the cities to prevent the sedimentation of solid materials in the city's regulating reservoirs. They generally consisted of large rectangular tanks or ponds with a bottom below the level of the canal, where sediment was deposited, and were usually equipped with a bottom drain for automatic cleaning (Adams 1994, 488–510).

Roman cities could be supplied by one or more aqueducts. Rome, the capital of the Roman Empire, had up to 11 main aqueducts with various branches. Some Roman aqueducts that have survived to the present day are a clear demonstration of the challenges overcome and the high level of hydraulic expertise of Roman engineering, such as the Zaghouan Aqueduct, which supplied the city of Carthage in present-day Tunisia, in the Figure 6, which is around 132 kilometres

Figure 6. Zaghouan Aqueduct, Tunisia, ©2021 architectureofcities.com.

Figure 7. Gades Aqueduct, Cádiz, ©2021 architectureofcities.com.

long, with some of its sections still in operation today; or the Gades Aqueduct, in Cádiz, around 75 kilometres long, most of which is a siphon, the latter being the longest Roman aqueduct in Hispania, see Figure 7 (Fortes 2008).

In the city, the distribution of water collected on the outskirts was regulated by storage reservoirs or *castellum divisorium*. In Portugal, an example of this type of reservoir can be found in Conimbriga, at the end of the aqueduct that supplied the city, mentioned above. It was a settling tower, a *castellum divisorium*, which functioned both as a settling tank and a siphon for changing the level/pressure of urban water distribution (Reis 2013).

Thus, the *castellum divisorium* was the place where the water supply ended and the distribution network began. It was usually a rectangular chamber with successive annexes; the roof had a barrel vault or grooved vault; the tanks had a water inlet and outlet; a bottom drain and a spillway connected to the city's sewers. The bottom of the reservoirs suffered from sedimentation and had to be cleaned periodically.

Later, the water was distributed through aqueducts, channelling, lead (fistulae or ceramic pipes, siphons, diverticula or water chests that served to divide and distribute the flow to the various parts of the urban network. Usually, water was distributed through three separate pipelines: one that served the thermal complexes, another for private homes and a third to supply the public network of fountains and springs(Ribeiro 2013) .

An example of a complex water distribution network was the one that supplied the public fountains in the city of Pompeii, where water was channelled through ceramic or lead pipes that ran underground, reaching a depth of 0.60 metres and supplying around 40 public fountains (Koloski-Ostrow 2001).

There was also a dense water distribution network in *Bracara Augusta*, well-illustrated by the underground aqueduct that supplied the public baths of Alto da Cividade, see Figure 8, built with walls of regular blocks, based on a brick ballast and covered by large stone slabs. This conduit had a specus about 0.60 metres high and 0.45 metres wide, clearly demonstrating the importance of its water flow. The structure's ballast and walls were clad in *opus signinum* (Figure 8c) and showed a slight N/S slope (0.10 metres over a 60 metre stretch) (Martins and Ribeiro 2012).

In any case, ceramic tubules and lead fistulas (*fistulae*) were widely and independently used for water distribution. They were in the shape of cylinders and had male/female ends (Figure 9b), which ensured that the pipes were watertight, also guaranteed by applying a mortar of quicklime mixed with olive oil to the joints (Vitruvius, VIII, VI, 8).

As in other Hispanic Roman cities, some of these ceramic pipes were discovered in Braga, mainly associated with the distribution of water to the thermal complexes. The identification of a lead pipe (*fistulae*) in the excavations carried out in the archaeological area of the *domus* das Carvalheiras, associated with the construction of a balnea, see Figure 8c, clearly demonstrates that this type of material was also used in the water distribution network of *Bracara Augusta*. The fistula that was discovered had a section at its widest measuring 141 mm horizontally and 146 mm vertically, and also showed signs of welding at the edges. Also worth mentioning are the various perforated siphon blocks found in various parts of the city, see Figure 9a (Martins and Ribeiro 2012).

3. Continuities and ruptures in the supply of water to the medieval city

With the end of the Roman Empire in the West, the fate of the Roman cities was very different: some ended up

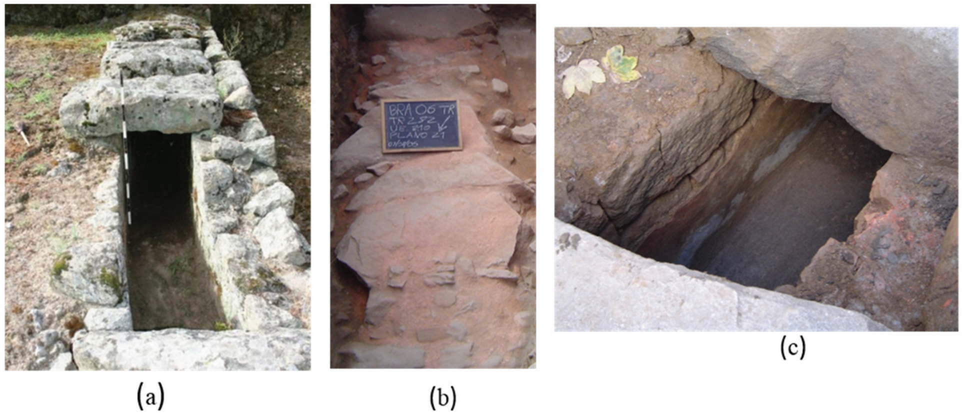

Figure 8. Water supply aqueduct of the Alto da Cividade thermal baths (Braga): (a) and (b) Aspects of the aqueduct. (c) Interior view of the aqueduct lined with opus signinum ©UAUM.

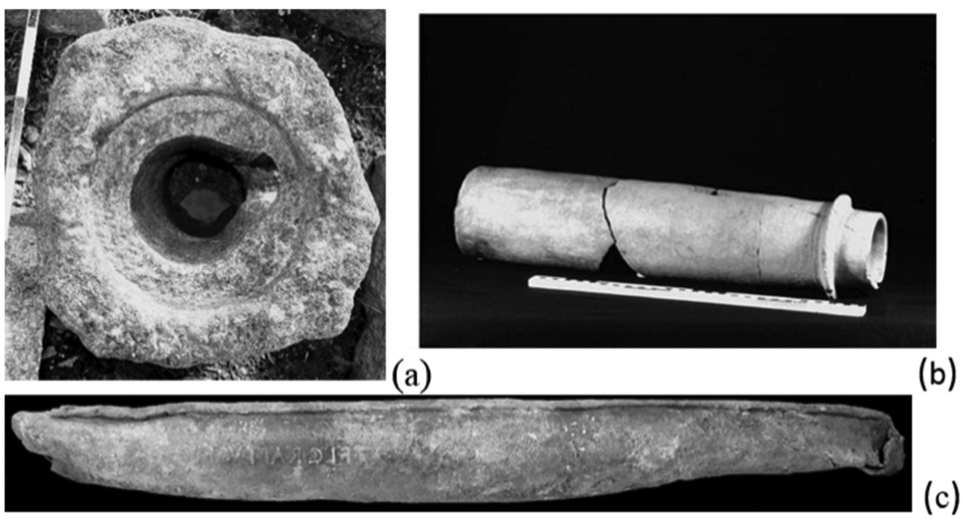

Figure 9. Water distribution elements: (a) perforated siphon block, (b) ceramic pipe, (c) lead pipe (fistulae) (Braga) ©UAUM.

disappearing, others survived, albeit with a large demographic and urban reduction, which naturally had repercussions in terms of overall water consumption. Also, despite the importance of water in Christianity, its adoption implied a profound change in the social and cultural habits of communities in Western Europe, which gradually ceased to value the same type of architecture and urban spaces as the Romans.

The water supply for urban centres in the High Middle Ages was largely made up of simple structures from which it was possible to collect the water available within the centre itself, whether surface or underground. The various forms of supply would change in quantity and quality as the urban centres themselves developed demographically and economically (Magnusson 2002).

As in Roman cities, the water used in urban centres was also rainwater, stored in tanks and cisterns. In the case of cisterns, we can mention the one in the castle of Chaves, which occupied the entire first floor, receiving rainwater from the roof through a stone duct attached to the wall. In Bragança there was also an identical cistern in the castle, and another under the slabbed structure on which the town hall was built in the early 16th century (Amaral and Noé 2012).

Although there may have been an abundance of surface water in some medieval settlements, flowing in open ditches through the streets, as the documentation shows for the cities of Coimbra, Leiria and Braga, the insufficiency of this water, whether rainwater or from springs that drew water from the surface, is well attested to by the reference to other forms of supply that required groundwater abstraction, such as wells (Ribeiro 2020).

The importance of these structures, although architecturally not very elaborate and limited in number, can be measured by the references preserved in medieval documentation, but also in the road toponymy of urban centres, with the designation of Rua do Poço (Street of Well). In general, these were private wells, distributed

Figure 10. Medieval well at Montalvão (detail), Duarte de Armas, Book of Fortresses, c. 1509.

Figure 11. Backrest fountain in Évora (detail), Duarte de Armas, Book of Fortresses, c. 1509.

throughout the urban space, located in domestic spaces, namely in the backyards of houses, but also municipal wells, for collective use, see Figure 10. There were cases in which the importance of these wells conditioned the location of the town itself, as was the case of the urban centre of Bemposta (Portugal), where in 1315 King Dinis ordered that a well be included in the walled perimeter (Trindade 2013, 151).

Water could also be distributed to the population by means of fountains, the typology of which was generally simple, sometimes referred to in the documentation as "cobertas" (covered) or "arcadas" (arcaded), called "mergulho" or "chafurdo", because they consisted of a tank, covered by a stone structure that could be vaulted to protect the water. Access to the tank where the bucket was dipped was down several steps, as in the case of the S. Geraldo Fountain in Braga, located below the courtyard of the Misericórdia Church, currently inaccessible. In this case, it was an underground fountain "set in a very well-made stonework arch . . . and its waters were excellent, considered miraculous" (Ribeiro and Martins 2012, 206).

Another type with a simple structure was the "espladar" (backrest) fountain, which was widespread at the end of the Middle Ages. Although they could be simple tanks attached to a vertical wall from which the water spout hung, they often included coat-of-arms and epigraphs, as can be seen in Alandroal or Évora (Portugal), according to the representation by Duarte de Armas, see Figure 11, but also in the Chafariz d'El Rei in Lisbon, or

Figure 12. Fountain of Granjinhos, Braga, Portugal, in present-days.

even like those built in Braga at the beginning of the 16th century, see Figure 12 (Ribeiro 2020).

Despite the variability in the number of water fountains in urban centres, as a general rule they were simple structures located at easily accessible points, near the gates of walls, roads or squares, with a tendency to increase and monumentalise them in the Lower Middle Ages (Leguay 2002).

In addition to their main function, it is also important to highlight the role played by fountains as a place for the urban population, particularly women, to gather and socialise, and in shaping the medieval urban scene (Ribeiro 2023).

Unfortunately, many of them have not survived to the present day. However, for example, the Chafariz dos Canos, in Torres Vedras (Portugal), a large fountain with a pentagonal structure, whose construction dates back to the 1320s (Noé and Rosa 2002), has been preserved, although probably altered, as has the Fountain of Granjinhos, in Braga, built by the archbishop D. Diogo de Sousa in 1531, in Figure 12 (Ribeiro and Martins 2012).

The insufficiency and difficulties experienced with the water supply in medieval cities in some periods are attested to in written sources, revealing not only the concerns to improve the supply of this essential commodity, but also the difficulties that existed in the general supply of water to the urban centre. A concrete example is in the city of Braga, in the 2nd quarter of the 15th century, where the water collected in the city, through wells or fountains, was not enough to meet all the needs of the city, and had to be collected on the outskirts, about a league away (approximately 5 kilometres), and taken "through covered stone pipes" to the city, to supply fountains, tanks and washhouses (Marques 1980, 129–30). In the case of the city of Braga, as in other realities, everything leads us to believe that we are dealing with the reuse of Roman aqueducts, which have never ceased to function, albeit with little or no maintenance (Ribeiro 2020).

The collection of water on the urban periphery and its conveyance via aqueducts to the medieval centres is also documented in the toponymy, which has made it possible to immortalise some of its routes within the walls, namely via "Rua dos Canos" (Water Pipe Street), and there is no shortage of examples in the medieval toponymy of streets/squares/fountain of Pipe, through or to which water flowed piped from springs sometimes located long distances away (Ribeiro 2020).

In addition to domestic use, washing clothes and watering animals, water was also essential for some of the economic activities needed to supply the medieval city, namely processing and production, such as those related to the supply of meat and fish, carried out in butchers' shops, the processing of hides and skins, as well as those related to maritime and river activities.

In reality, water had its greatest presence in medieval urban centres through the waterways. As a general rule, rivers are associated with a series of activities related to fishing and navigation, as well as their exploitation as a hydraulic force to move mills, for example.

However, one of the most noteworthy aspects of the almost constant presence of watercourses in medieval centres is related to the urban development they fostered, as well as the establishment of socio-environmental dynamics resulting from their exploitation and use. In this respect, the cities of Lisbon and Porto are paradigmatic examples. Alongside the Tagus and Douro rivers, respectively, these urban centres benefited from their proximity to the sea. In both Lisbon and Porto, the riverside area along the respective rivers has played a major role in their development since human occupation, fuelling the affirmation and consolidation of both cities in the medieval period.

Despite the existence of a high walled centre, located on top of hills, in the case of Lisbon, corresponding to the current hill of S. Jorge, and in Porto, the hill of Pena Ventosa, the natural characteristics of these riverside areas would have been a strong attraction for commercial, productive and harbour activities related to river and sea navigation, and consequently for the construction of support infrastructures, gradually becoming important areas of extra-mural growth, or the lower city, whose importance has continued to the present day.

In the case of Lisbon, see Figure 13, the bustling riverside area, located to the west of the medieval high

Figure 13. Lisbon riverside area (detail Braun – Hogenberg, 1572).

walled centre, can be traced back to the 13th century, when it was home to various naval facilities, such as the Tercenas (shipyards), the Casas das Galés (Galley Houses), some industries such as the Ferrarias Régias (Royal Blacksmithing), the palace of the notaries, the customs house or the weight house, as well as other facilities relevant to the city, related to various commercial activities, such as the fish and meat market, held in the butcher's shops Silva (Silva 2017, 313–33)[19].

As in Lisbon, the Douro River and its proximity to the Atlantic Ocean also boosted the urban development of the Ribeirinha area in Porto, where, at least from the end of the 13th century, there was a concentration of commercial, productive and port activities, which had repercussions on the urbanisation of the lower part of the city, which was included in the 14th century walled perimeter bordering the river (Ribeiro and Melo 2023).

However, we are talking about cities whose supply needs and consequently their importance as a centre of consumption, production and distribution are intertwined with those of the kingdom itself.

In most of the other towns, the supply was on a much smaller scale and the watercourses allowed for more limited economic activities. We are referring, for example, to animal skin production work, but also in many cases to the slaughter and sale of animals. In the case of Braga, leather production was also established, at least since the 14th century, along the East River, located outside the walls, at the end of Rua dos Pelames, next to the bridge of the same name, which crossed the East River and provided a link to Porto, see Figure 14. As we can see from the existence of 37 leather tanning tanks tanneries in the mid-15th century, this would have been a very important economic activity for the city, just like in Guimarães (Portugal), a city that today preserves some important architectural heritage related to the leather tanning, next to the river of Couros, classified as a world heritage site, see Figure 15.

Figure 14. Braga East River (detail Braun – Hogenberg, 1594).

Figure 15. Leather tanning tanks, Guimarães, Portugal.

4. The main challenges facing modern cities in the field of hydraulic construction

The demographic and economic growth experienced by cities from the end of the 15th century onwards helped increase the medieval need to find new places to supply water, whether within the urban space or on the outskirts. In a large number of Portuguese cities, successive improvements and extensions were made to the water supply, in line with urban development itself, either by opening new wells or by renovating, improving and embellishing existing fountains.

There was also greater care and visibility of the water supply structures, giving rise to more striking architecture, particularly in the case of aerial aqueducts, but also highly monumentalised fountains. In the case of aqueducts, takes place the construction of the great aqueducts that are still visible today along most of their route, such as the Torres Vedras aqueduct or the Água da Prata Aqueduct in Évora (1530), the latter built on the structure of the old Roman aqueduct by the architect Francisco de Arruda, as well as a water tank built in Rua Nova by Miguel de Arruda (Branco, Nunes, and Bandeira 1996), to receive water and later distribute it to different parts of the city, including public fountains.

In fact, in parallel with the concerns and regulations regarding the supply of water to the population, the reign of King Manuel I saw several reformulations of hydraulic systems, namely fountains, but also the construction of new ones, such as the Chafariz d'El Rei in Évora (Amendoeira 1999).

In general terms, with the advent of the Renaissance, the fascination with classical culture allowed some dormant knowledge to be revived, namely through the re-reading of Vitruvius' work and consequently the birth of the treatise, but also water once again acquired an extremely important role in urban settings, where many newly opened or existing squares were decorated with fountains, some of which were monumental. For example, in Braga, in the early 1500s, Archbishop D. Diogo de Sousa ordered the opening of several new squares where fountains bearing his coat of arms were erected, such as the Fountain of Granjinhos, see Figure 12 (Ribeiro and Martins 2012).

Naturally, the abstraction of groundwater through boreholes in cities continued throughout the modern era. In some cases, the number of water wells reached quite high proportions. For Braga in the 18th century, which had around 17,000 inhabitants, the existence of more than 800 wells is reported, mostly in backyards, gardens and vegetable plots (Ribeiro and Martins 2012).

A distinction must necessarily be made between catchments for domestic/private use, such as the wells mentioned in the documentary sources, and public supplies such as fountains, washhouses or tanks.

With regard to wells, it should be noted that in some cases it was the tenants themselves who were obliged to build them, although under certain conditions, namely where they had to be built, usually in the backyard, and how deep they had to be (Ribeiro and Martins 2012). The way in which water was extracted from the wells also varied, directly with the use of wooden buckets, but also with the use of a waterwheel, as illustrated for Braga in Figure 16. Some of these wells, like the one in Figure 17, have a circular plan and a masonry structure made up of large and medium-sized granite blocks, topped by large granite blocks.

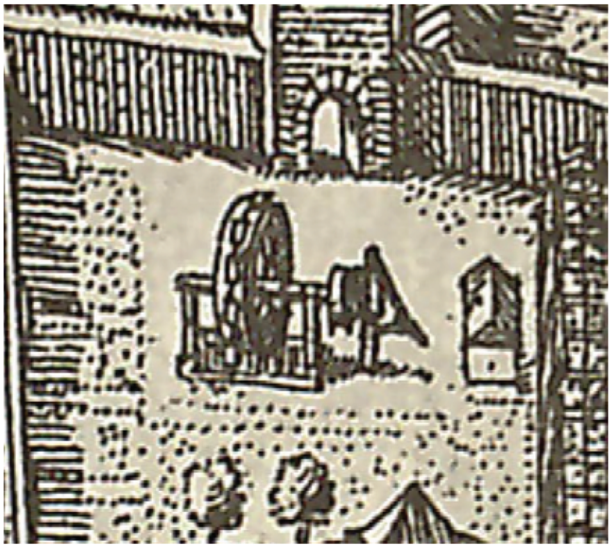

Figure 16. Waterwheel (Nora), Braga, (detail Braun - Hogenberg, 1594).

Figure 17. Modern well exhumed during archaeological excavations in Braga ©UAUM.

Like wells, the number of fountains in cities also increased significantly throughout the Modern Age. Once again, we turn to the example of Braga, a city in which the existence of more than 70 perennial fountains, both public and private, is mentioned for the 18th century. Some of these fountains have elaborate architecture, such as the Porta do Souto fountain and the S. Sebastião fountain, and are sometimes richly ornamented, with mentions of who commissioned them or the city's coat of arms. The backrest or body (in the case of fountains that are attached) is the part of the fountain that gives it the greatest visibility in the urban space and plays an important role in the city's image. Some of them pour water through 6, others through 4, others through 2 spouts (Ribeiro and Martins 2012), as illustrated in Figure 18.

In fact, throughout the 17th and 18th centuries, alongside urban planning, urban authorities continued to give a special place to water works, namely the construction of new water sources, or the repair of existing ones, as well as the creation of water conduction systems, which at the time sometimes flowed abundantly and freely through the ground, as was the case in Lisbon or Braga (Ribeiro 2020).

But it was especially in the 18th century, with the great urban and population growth in urban centres, that the need to collect water from the outskirts in large volumes became effective, leading to the construction of aqueducts or the rehabilitation of what had survived from the Roman aqueducts. The use of aqueducts significantly altered the water supply system for cities, as was the case in Lisbon with the construction of the Águas Livres Aqueduct in the second quarter of the 18th century, or in Braga with the Sete Fontes Aqueduct.

Figure 18. Fountains from the Modern Age in Braga, Portugal.

However, as was the case in antiquity, the use of aqueducts meant overcoming various challenges to get the water from the springs to the city, which involved highly complex technical work, but also economic resources that could only be overcome through the public purse. For this reason, from the design of the aqueduct to the start of construction could take several years, involving various players, including renowned designers and military engineers.

In the case of Lisbon's Águas Livres Aqueduct, the construction of which involved several architects and military engineers, as well as a royal tax to contribute to the works in 1729, the main section is approximately 14 kilometres long, but has several subsidiary aqueducts and supply galleries, making up a network of approximately 58 kilometres. Throughout its course, water is transported by gravity. It is located underground or close to the surface, but when it crosses deeper valleys, it has a perfectly round arch, with a depressed or broken arch, as is the case with the 14 arches pointing over the Alcântara Valley, which are still visible today (Caseiro, Pena, and Vital 1999). In the case of the Sete Fontes Aqueduct in Braga, the water is collected at a distance of approximately 3.5 kilometres, through 14 underground galleries (water mines) and 6 circular junction tanks, from where the water comes out and is gravity-fed to the city through an underground conduit, the entire complex being made of worked granite stone.

In Vila do Conde we find the second longest 18th century aqueduct in Portugal, made up of 999 arches, which supplied a religious building, the convent of Santa Clara. Efforts to build it began in 1626 on the initiative of the then abbess, but the water didn't reach the convent until 1714, partly due to successive economic problems and work stoppages. A decisive impetus for its finalisation came with the design of a new aqueduct project by the king's engineer, Manuel Pinto de Vila Lobos. A large part of the original structure still remains, formed by a set of broken granite arches of decreasing height, with the upper profile of the channel rounded off (Freitas 1961)

It was essential that water collected from distant areas reached an urban distribution reservoir, from where it was distributed to different parts of the city. These reservoirs could be simple water tanks or large tanks, such as the Mãe de Água Reservoir in Amoreiras, Lisbon, built between 1746 and 1834. The latter, now part of the Water Museum, had a large cistern inside that received and distributed water from the Águas Livres Aqueduct in Lisbon, built by King João V (1707–1750) (Caseiro, Pena, and Vital 1999).

It was also during the reign of King João V that the great aqueduct of the city of Rio de Janeiro in Brazil was inaugurated, known as the Carioca Aqueduct, in Figure 19, considered one of the greatest works of the colonial period, which took more than a century to complete and was inaugurated in 1726 (Azevedo

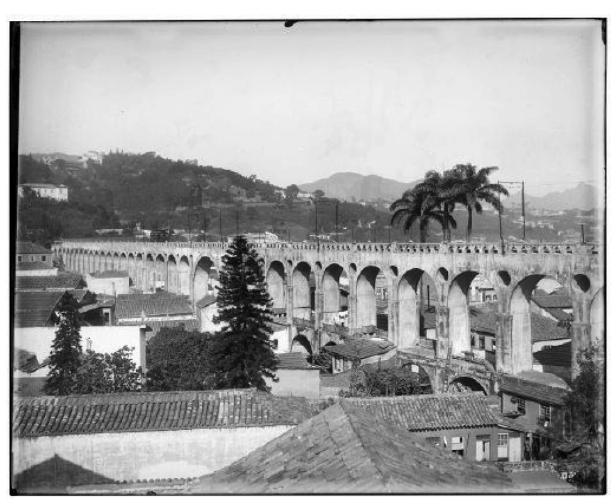

Figure 19. Carioca Aqueduct, Rio de Janeiro, Brasil (Marc Ferrez, 1896, Acervo Instituto Moreira Salles).

2023). This aqueduct, with similarities to the Águas Livres Aqueduct in Lisbon, began in a large masonry water tank, still known today as Mãe de Água, located near the Carioca River, and descended through a two-metre-high, all-stone culvert, with sections preserved today, It passed under a chapel (now the Convent of Santa Teresa), from where it followed masonry arches to the hill of Santo António, supplied the Franciscan convent and descended by ramp to the Carioca square and ended at the famous baroque stone fountain, which had sixteen stone frowning heads through which water poured (Azevedo 2023).

In the case of Braga's water aqueduct, the general water tank was a tall stone structure made of frames, which had a large arch inside where the water entered. Water from different places flowed into it and from there it was redistributed to the urban centre via five pipes, which channelled water to five different places. The main source of water for this box was the springs located in the hills to the north-east of the city, known as Sete Fontes. The water was then conveyed by stone pipes and tarns to the general reservoir. The material existence of the conduit that came from the Sete Fontes aqueduct is still visible today on the surface in the catchment area, monumentalised with the construction of water mothers in the 18th century, see Figure 20. Assuming that some of the Roman water pipes were successively reused until the Modern Age, it is also presumable that this general water tank may have resulted from the reuse of a Roman water castle (Ribeiro and Martins 2012).

The type of pipework was equally varied, although they were generally stone pipes, with the terminology in the documentary sources oscillating between aqueducts, pipes, stone pipes, gutters and stone-covered gutters. There were also water distribution boxes and spouts scattered around different parts of the city. Some of these examples can still be seen in the city, as can be seen in Figure 21, and it is known that some sections of the Sete Fontes aqueduct were in operation until the 19th century or even earlier. The places where the different public water pipes ran are quite different. Some ran along the streets, others through backyards and vegetable gardens, still others under houses, and it is known that the owners of the houses where the water pipes ran were obliged to keep them clean and clear (Ribeiro and Martins 2012).

Figure 20. 7.Fountains Aqueduct, Braga, Portugal.

Figure 21. Modern water tank, water pipe and washbasin in Braga, Portugal.

5. Concluding remarks

The collection and supply of water was a central theme in the political, social and economic organisation of cities from Roman times to the modern age, which led to the adoption of disparate building solutions that strongly marked the configuration of urban landscapes. In some cases, these construction solutions were successively reused, leaving material evidence to this day that can be studied by archaeology.

The study of the constructive challenges posed by the supply of water to Roman cities in Portuguese territory has been evaluated on the basis of the archaeological remains that have survived, as well as studies of a palaeoenvironmental and geohydrological nature.

Today, as is the case in other geographies, it is possible to prove that the location chosen by the Romans for the foundation of new cities in Portuguese territory took into account the region's water resources, thus endeavouring to safeguard the high consumption of Roman urban society.

Tanks, particularly those found in houses (*domus*) (*impluvium*), were a common form of rainwater supply in Roman cities, as well as that which flowed into rivers or streams, sometimes through cisterns, and these were the primary forms of supply. However, it is clear that the quantity, regularity and quality of rainwater was not enough to supply the Roman urban centres, which led to it being collected from natural sources, which flowed underground or deep underground, through wells and fountains in the urban centre itself, which in a phase of low demographic and economic density may have been the main form of supply, but with a limited response capacity as the urban growth process thickened, the solution was to collect water from distant places through aqueducts.

Whatever the solution, identifying the ideal places to collect water would require careful knowledge of the terrain and experienced people, requirements that were equally crucial when building aqueducts to supply large population centres with regular, clean water in sufficient quantity. Equally important was the economic issue, since topographical accidents were common between the source and destination of the water, which Roman engineers had to solve by combining different types of construction solutions underground, above ground and/or overhead, combining various types of structures such as underground and above ground ducts, tunnels, bridges and siphon systems.

In most of Portugal's medieval cities, especially those of Roman origin, the Roman water supply systems were discontinued and many aqueducts were demolished, with the stones being used to house different types of buildings, such as walls, palaces, or churches. In reality, the amount of water needed decreased significantly as a result of the decline in the urban population and water use in the Middle Ages.

The solutions found to supply medieval Portuguese settlements were mainly the rainwater, the water that flowed in rivers or streams, and the use of groundwater or surface water existing within the settlement or in its vicinity, namely through wells and water fountains. However, with the densification of the urban growth process and economic development since the end of the Middle Ages, these solutions became insufficient, leading to the need to search for water in distant places and transport it via aqueducts to the urban centres. However, in many cases the supply sites were the same as those used by the Romans, and some of the structures used to convey water, namely underground and surface pipes, were reused.

But the challenges of supplying large quantities of water to cities in the Modern Age led to the construction of new aqueducts, whose construction techniques benefited from the knowledge acquired by the Romans, but also from those developed from the Renaissance onwards throughout Europe and which Portuguese military engineers and architects applied to constructions in Portuguese territory, but also in other geographies such as Brazil.

Some of the supply systems built in the Modern Age in Portugal remained active until the 20th century, undergoing successive improvements, in a clear demonstration of their efficiency, allowing large quantities of water to be transported to the cities to supply the population, namely through the numerous architectures that allowed their distribution, as public water fountains, which from the Renaissance onwards and throughout the Baroque period were given a more lavish structure, the result of elaborate sculptural and architectural form and decoration, providing embellishment and the creation of scenic spaces that catheterise modern urban landscapes.

In all periods of history, the challenges posed by the supply of water to cities have been multiple, as have the construction solutions varied, and it is true that the water heritage has undergone successive changes over time, partly due to successive use, renovation and improvement, as evidenced by certain supply systems, with permanence from Roman times to sometimes the 20th century.

Data availability statement

The data will be made available upon request by contacting the corresponding author.

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References

Adams, P. 1994. *Roman Building. Materials and Techniques*. Lodon: R. T. Batsford Ltd.

Amaral, P., and P. Noé. 2012. Câmara Municipal de Bragança/ Domus Municipalis. SIPA. http://www.monumentos.gov.pt/Site/APP_PagesUser/SIPA.aspx?id=2418 .

Amendoeira, P. 1999. Chafariz Del-Rei. SIPA. http://www.monumentos.gov.pt/Site/APP_PagesUser/SIPA.aspx?id=8854.

Azevedo, M. 2023. *Aqueduto Da Carioca e Chafariz de Dom Pedro II: Trechos Selecionados de O Rio de Janeiro/Moreira de Azevedo*. Rio de Janieo: Pop Stories.

Braga, C., and J. Pacheco. 2013. *Relatório Dos Trabalhos Arqueológicos Realizados No Campus de Gualtar Da Universidade Do Minho. Relatório Do Ano de 2006*. Braga. https://hdl.handle.net/1822/24749.

Branco, M. B., C. Nunes, and F. B. Bandeira. 1996. 'Aqueduto Da Prata/Cano Da Água Da Prata'. Sipa. Sipa. http://www.monumentos.gov.pt/Site/APP_PagesUser/SIPA.aspx?id=2755.

Caseiro, C., A. Pena, and R. Vital. 1999. *Histórias e Outras Memórias Do Aqueduto Das Águas Livres*. Lisboa: EPAL.

Cravo, J., and H. Bonifácio. 2010. 'Aqueduto Romano de Conimbriga e Castellum de Alcabideque'. http://www.monumentos.gov.pt/site/app_pagesuser/sipa.aspx?id=2677 .

Fortes, M. 2008. *A Xestión Da Auga Na Paisaxe Romana Do Occidente Peninsular*. Santiago de Compostela: Universidad de Santiago de Compostela. http://hdl.handle.net/10347/2532 .

Freitas, E. D. A. D. C. 1961 Boletim Vila Do CondeO Aqueduto de Santa Clara de Vila do Conde. Separata do N. 2 do Boletim Cultural de Vila do Conde. Barcelos: Tipografia Vitória.

Garrido Elena, A., R. Mar, and M. Martins. 2008. *A Fonte Do Ídolo. Análise, Interpretação e Reconstituição Do Santuário*. Braga: UAUM/CMB/ICAC.

González Tascón, I. V. 2004. *Ingeniería Romana En Hispania. Historia e Técnicas Constructivas*. Madrid: Fundación Juanelo Turriano.

Koloski-Ostrow, A., ed. 2001. *Water Use and Hydraulics in the Roman City*. Boston: Archaeological Institute of America.

Leguay, J.-P. 2002. *L'eau Dans La Ville Au Moyen Âge*. Rennes: Presses Universitaires de Rennes.

Magalhães, F. 2019. *A Domus Romana No NO Peninsular. Arquitetura, Construção e Sociabilidades*. University of Minho. https://hdl.handle.net/1822/64109.

Magnusson, R. J. 2002. *Water Technology in the Middle Ages. Cities, Monasteries, and Waterworks after the Roman Empire*. Baltimore: Johns Hopkins University Press.

Marques, J. 1980. D. Fernando Da Guerra e o Abastecimento de Água à Cidade de Braga No 2° Quartel Do Século XV. *Mínia* 3 (4):127–37.

Martins, M., L. Fontes, and A. Cunha. 2013. Arqueologia Urbana Em Braga: Balanço de 37 Anos de Intervenções Arqueológicas. In Arnaud, J. M., Martins, A., and Neves, C. (Eds.), *Arqueologia Em Portugal. 150 Anos* (pp. 81–88). Lisboa: Associação dos Arqueólogos Portugueses.

Martins, M., and M. C. Ribeiro. 2012. Gestão e Uso Da Água Em Bracara Augusta. Uma Abordagem Preliminar. In *Caminhos Da Água*, ed. I. F. Manuela Martins, and I. Valdivieso, 123–56. Braga: CITCEM. https://hdl.handle.net/1822/19872.

Middleton, J. H. 1892. *The Remains of Ancient Rome*. Universidade de, MI: A. and C. Black.

Noé, P., and A. R. Rosa. 2002. Chafariz Dos Canos. SIPA. http://www.monumentos.gov.pt/Site/APP_PagesUser/SIPA.aspx?id=6347.

Porfyriou, H., and L. Genivese, eds. 2012. *Water Shapes. Strategie Di Valorizzazione Del Património Culturale Legatto All'acqua*. Roma: Palombi Editore.

Reis, M. P. 2013. "Gestão e Rede Hidráulica de Conimbriga A Domus de Tancinus e Construções Anexas". In *CONIMBRIGA TARDO-ANTIGUA Y MEDIEVAL. Excavaciones Arqueológicas En La Domus Tancinus (2004-2008)*, ed. J. L. Quiroga, 25–36. Oxford: BAR International Series 2466.

Ribeiro, J. 2013. *'Arquitectura Romana Em Bracara Augusta. Uma Análise Das Técnicas Edilícias'*. Arquitectura Romana Em Bracara Augusta. *Uma Análise Das Técnicas Edilícias*. Universidade do Minho. doi:10.21747/9789898351272/arq2013.

Ribeiro, M. C. 2020. Espaços e Arquiteturas de Abastecimento Da Cidade Medieval. In *Provisioning Medieval European Towns*, 383–402. Lisboa: IEM/C.M.C.V. https://hdl.handle.net/1822/67740.

Ribeiro, M. C. 2023. A Mulher Portuguesa Na Cidade Medieval: Exceções Que Fazem a Diferença. In *La Edad Media En La Europa Meridional. Gentes, Procesos y Dinámicas*, ed. R. G. González, R. Peñín, and S. P. González, 46–65. León: Servicio de Publicaciones de la Universidad de Huelva.

Ribeiro, M. C., and M. Martins. 2012. 'Contributo Para o Estudo Do Abastecimento de Água à Cidade de Braga Na Idade Moderna. O Livro Da Cidade de Braga (1737)'. In *Caminhos Da Água*, ed. I. F. Manuela Martins, and I. Valdivieso, 179–222. Braga: CITCEM.

Ribeiro, M. C., and A. Melo. 2023. A Influência Das Actividades Económicas Na Organização Da Cidade Medieval Portuguesao. In *Evolução Da Paisagem Urbana: Transformação Morfológica Dos Tecidos Históricos*, ed. M. C. Ribeiro, and A. Melo, 183–222. Braga: CITCEM/IEM. https://hdl.handle.net/1822/23984.

Rodrigues, A. D., Marín, C. T. 2020.*The History of Water Management in the Iberian Peninsula*. In Rodrigues, A. D. and C. T. Marín (Eds.), Between the 16th and 19th

Centuries. Cham: Springer N. Birkhäuser. https://doi.org/10.1007/978-3-030-34061-2.

Silva, M. F. 2017. *Mutação Urbana Na Lisboa Medieval. Das Taifas a D. Dinis*. Universidade de Lisboa. http://hdl.handle.net/10451/29987 .

Trindade, L. 2013. *Urbanismo e Composição de Portugal*. Coimbra: Imprensa da Universidade de Coimbra. https://hdl.handle.net/10316/13529 .

Trindade, L. 2014. A Água Nas Cidades Portuguesas Entre Os Séculos XIV e XVI: A Mudança de Paradigma. In *Patrimonio Cultural Vinculado Con El Agua. Paisaje, Urbanismo, Arte, Ingeniería y Turismo*, ed. M. L. Bartolozzi, and V. M. Hernán, 376–380, Mérida: Editora Regional de Extremadura. https://hdl.handle.net/10316/79514.