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The Roman Aqueduct of Lisbon: A Utopia or a Viable Enterprise?

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Abstract

The first references to the *Olisipo* aqueduct date from the 16th century and regard the *Águas Livres* springs and the *Belas* Roman dam. During the 17th and 18th centuries, architects and engineers reported the existence of remains of an old conduit. However, the lack of physical archaeological proof in Lisbon area led some researchers to consider the *Olisipo* aqueduct a utopia idea. Supported by documentation and functional interpretation of Roman hydraulic structures, tests to find out the aqueduct route were developed through an innovative geographic modelling. Different surfaces of topographic conditioning were generated to create a viable route for the water to be conveyed to both *termini* of *Olisipo* referred to by the royal architect Leonardo Turriano.[*]

Felicitas Iulia Olisipo: Brief Overview of the Urban Structure

According to documentary and archaeological sources, the area corresponding to the old city centre of Lisbon was rather important in protohistory. This settlement, with oriental influences, was probably founded in the 7th century BC (or even earlier) and is currently considered the one with the largest area in the peninsular Atlantic seaboard.[1] It was called *Olisipo* and in the first half of the 2nd century BC it was an important *Turdulorum oppidum*.[2] It was integrated into the Roman sphere in 138 BC[3] and its municipal promotion occurred between 31 and 27 BC, involving an urban planning program that included a founding wall, the construction or renovation of public facilities, in short, a redesign of its urban morphology.[4] According to Pliny, the city's full name was *Felicitas Iulia Olisipo* and was considered a *municipium civium Romanorum*.[5] Thanks, not only to this new status but also to its role as a *caput viarum*, and to the excellence of its port as well as its social structure, it became the real seaside capital of Lusitania.[6]

The delimitation of the *pomerium* and of its surrounding *suburbia*, Roman urban entities with different identities and features, were only ascertained with a certain degree of accuracy, thanks to recent analytical studies.[7] The first one was limited by a foundation wall, of which it was possible to identify a few sections, and had some habitat sectors, located mainly close to the castle of São Jorge and in the area of the Cathedral's cloisters; furthermore, it was found that the hill was organized according to different terraces intended to be used for construction.[8] The main public facilities that have been identified so far are the theatre, possibly built shortly after the end of the reign of Augustus, the Cassian Baths built in the second half of the 1st century AD[9] and the Temple of Cybele which was probably integrated into the municipal *forum.*[10]

In the eastern *suburbia* it is possible to identify in the urban area a fossilized regular grid with a Roman metrics.[11] This area was crossed by a section of the *Olisipo* - *Scallabis* road, along which there were several necropolis.

In the western *suburbia*, an area dominated mainly by port-related activities, two important public structures have been identified to date - the circus (mid-1st century AD or 2nd century AD)[12] and a *cryptoporticus* associated with a corporative *forum*[13] or with a sanctuary of Asclepius,[14] in addition to numerous industrial facilities related to salt-fishing products from which we highlight the complex on Correeiros Street. Most of these units were built along the margins of the Tagus River and the Baixa branch where the harbor was located or in their surroundings. The main structuring axes of this *suburbia* were the north road, associated with the northwestern necropolis (Figueira Square) and the western road perpendicular to the latter (*fig. 1*).

One of the most curious aspects of *Olisipo*'s urban dynamics has to do with the settlement on top of the hill (Castle of São Jorge). From the end of the Late Republic onwards, that area became increasingly depopulated, a fact that, according to several authors can be explained by the trauma caused by the military occupation which occurred in the late 2nd century BC.[15] There were also important urban changes during the Late Empire.

Fig. 1. Reconstitution 3D of Olisipo *by César Figueiredo (2015) (source: picture provided by the author).*

A defensive wall, of which several sections have already been identified, was built in the early 4th century with its South and East sectors being used as foundations for the primitive medieval wall (Cerca Moura or Moorish Wall). The last third of the 3rd century AD witnessed a 'demonumentalization' that affected mainly the northwestern necropolis, the circus and the theatre.[16] Between the late 4th century AD and the 6th century AD there was a widespread appropriation of old public spaces and most of the fish processing units closed down until the mid-5th century AD.[17]

Despite these signs of decadence, others suggest that *Olisipo* was still a major port during the Late Empire and that there was even an intensification of maritime activities, namely long-distance navigation. From the mid-3rd century onwards, except for *Hispalis* an inland port, *Olisipo* was undoubtedly the most important Atlantic port between the Strait and Aquitaine.[18] The city's importance throughout the Imperial period resulted, not only from the fact that it was a center of attraction and a hub for the reception of products that arrived by sea, but also from the fact that its harbor exported several products, especially the salt-fishing ones.[19]

Finally, we should mention that despite the information that has become available thanks to various archaeological interventions carried out in the old city centre of Lisbon many doubts about the nature and the structure of the Roman city remain.[20]

Main Structures Related to the Use of Running Water

This chapter presents an overview of the current knowledge on *Olisipo*'s hydraulic structures particularly the ones aimed at the use of significant volumes of running water (*fig. 2*).

Numerous old printed or handwritten sources have references to important hydraulic structures such as thermal baths,[21] the aqueduct which brought water to the city from the Carenque site, and the so-called *Olisipo* dam which supplied the aqueduct (*fig. 3*). References to canals, wells and springs located near the river are also common. We should also highlight the fact that our knowledge has been significantly increasing over the last few years as a result of the information provided by archaeological excavations carried out in the *pomerium* and, particularly, in the western *suburbia*.

In regards to thermal baths, the type of urban hydraulic unit that generally required a higher permanent flow, it has been possible to identify two units inside the *pomerium*: the public baths known as Cassian Baths and a small unit whose status remains undetermined.[22] From the western *suburbia* we should highlight the *cryptoporticus* (Prata Street) that, according to several authors, might

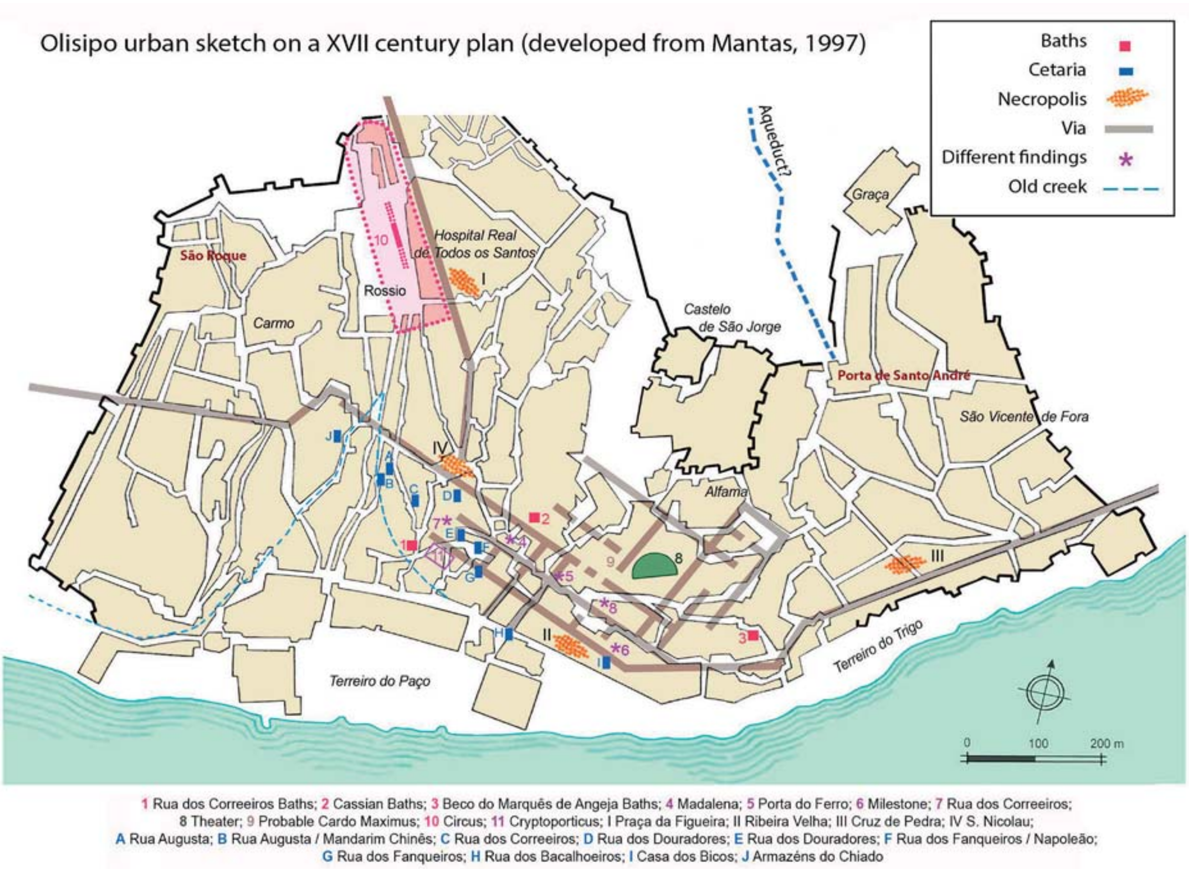

Fig. 2. Olisipo *schema over a map by João Nunes TinocoVasco (XVII century) showing the main water-use structures (based on Mantas 1997, 26 fig. 3).*

Fig. 3. Chelas or Olisipo *Roman dam, close to Águas Livres springs (photo José Manuel de Mascarenhas).*

have included public baths and the private baths integrated into the Correiros Street complex.

Undoubtedly, the building known as *Thermae Cassiorum* was, for its size[23] and decorative richness, one of the most important in *Olisipo*.[24] Its construction is traditionally attributed to *Quintus Cassius Longinus* and his brother *Lucius Cassius*. It was built before BC 49 and operated until the 4th century AD.[25] The first section of the building was discovered in 1771/1772 on Pedras Negras Street and announced by Father D. Tomás Caetano de Bem who, in a manuscript,[26] highlights an integrated set of three apse-shaped tanks.[27] This document also mentions that no drainage pipes had been found but that there was a common supply pipe. On the other hand, a NE-SW sewer with stone walls and a barrel vault and with an average height of 1.20 m and 0.60 m wide[28] was found in an internal circulation corridor. These figures allow inferring that the volumes of water involved were substantial so everything suggests that the supply of this thermal structure could only have been ensured by an aqueduct fed by a source located outside the city.[29]

Still inside the *pomerium*, in the Marquês de Angeja Deadlock, an archaeological excavation allowed discovering an apse which comprises what it thought to be an *alveus* and probably belonged to the *frigidarium* of a thermal complex.[30] These baths were built after 80 AD, in the last years of the 1st century or in the early 2nd century, and were no longer operating in the 4th century AD.[31] The origin of the water that supplied this complex remains unknown but we should not rule out the possibility that it was related to the water table of the spring of the Chafariz d'El Rei which was initially located inside the wall, and 'surely existed in the period of the Roman domain'.[32] But, given that is it nearly 160 m away (on a plane) from the location of the primitive fountain and approximately 25 m higher on the hillside, we should also consider the possibility that the water might have come from the aqueduct under study.

Another thermal complex identified in the course of an archaeological excavation was located in the western *suburbia* and integrated into an industrial fish-salting unit[33] which is currently the Rua dos Correeiros Archaeological Nucleus. This complex was located on a beach on the left margin of the river branch, which corresponded to the main hub of the port of *Olisipo*, and operated between the 1st century AD and the mid-5th century AD.[34] This unit was restructured during the 3rd century AD when the warehouses were replaced by a high-quality residential complex with its own thermal baths.[35] The only area that was analyzed was the *frigidarium* which comprised a square atrium with a polychrome mosaic pavement that allowed accessing four cold water tanks.[36] Probably, these houses that were integrated into industrial complexes (or located in their surroundings) belonged to their owners or managers. The thermal baths were probably supplied by water conveyed by an aqueduct whose source remains unknown. It can be assumed that it was a derivation of the São Roque branch of the *Olisipo* Aqueduct, or that it came from a weir located in the Valverde Stream.[37]

Another structure from the western *suburbia* that according to certain authors might have included thermal baths is the *cryptoporticus* on Rua da Prata (Silver Street). Built between the late 1st century BC and the early 1st century AD, it was identified for the first time in 1770 and known as 'Prata Street' or 'Augustales Thermal Baths' for a long time. Thomaz Caetano de Bem was the first to suggest that it might have been used for that purpose assuming, incorrectly, that it was an extension of the Cassian Thermal Baths.[38] In 1859 it was possible to ascertain that it was a complex of galleries that supported a large building of which only a very small section of a thick wall remains, in addition to tanks decorated with *opus signinum.*[39] Given that it was not an industrial fish-salting unit since several framed marble slabs were found inside suggesting the existence of noble claddings,[40] we may consider the possibility that there were thermal baths on top of the *cryptoporticus*, taking the aforementioned tanks into account. However, those tanks could have been part of either a bathing facility or a *forum.*[41] But the possible existence of thermal baths was strengthened by the discovery of an inscription dedicated by two Augustales, to Asclepius,[42] the god of health and medicine. Furthermore, the local groundwater and the so-called Águas Santas (Holy Waters) Well became famous for their curative and miraculous properties.[43]

Another structure whose water consumption may have been somewhat relevant was the *circus*, located under the Rossio Square, which was probably built in the 2nd century AD or maybe in an earlier period.[44] Along the continuous barrier (*spina*) that divided the arena into two tracks there was typically a series of water basins (*euripes*) that, aside from their decorative purpose, given that they often included statues, could also be used to water the horses.[45] While we can admit that occasionally, on specific dates (competition dates), there was a high water consumption, we do not believe that there would have been the need to ensure a constant flow of water,[46] except if the *euripes* worked permanently as fountains with jets. In that case, we could assume that the supply was insured by the São Roque branch of the *Olisipo* Aqueduct, allowing the water to arrive under pressure and operate the jets.

Among other hydraulic structures that might have been operated by a constant flow of water we should highlight fountains such as the one discovered during an archaeological excavation at the old Sommer House. It was built in the 5th century AD and drained water onto a slabbed pavement that shows clear wear marks.[47]

Among other facilities that have already been identified and needed water to support the activities that were carried out in them, we should highlight the numerous industrial salt-fishing units that were mentioned above. However, these did not need a permanent flow of water and resorted to water collected from wells, as other similar facilities such as the ones located in *Cetóbriga* (Setúbal), Tróia (Grândola) and Pessegueiro Island (Sines).

Águas Livres: The Origin of a Water Supply System for Olisipo?

While it is certain that King Duarte (1391-1438) read Marcus Tullius Cicero, Seneca or Aristotle in Portuguese in the early 15th century[48] and the city of Évora was already showing with pride it's Latin origins in 1501[49] - facts that suggest an early contact with the classical legacy through the books that were only available to the educated classes -, the truth is that the widespread fascination with 'antiques' was mostly a result of the survival of monumental structures, particularly the ones from the Roman period. Among them, aqueducts, with their impressive *arcuationes,* managed to solidly stand the test of time as symbols of a lost urbanity that the Christian princes, by education and need, wanted to retrieve even before the arrival of Humanism, the classicist and a fondness for the antique in the mid-16th century. That was the case of Queen Isabel, the Catholic, who between 1484 and 1489 promoted the restoration and reactivation of the Roman aqueduct of Segovia and created a code of *Ordenanzas*[50] for its proper management. We should also note, around the same time (*ca* 1490), King John II's inconsequential attempt to convey the famous 'Água da Prata' (Silver Water) to Évora along the topographic route of the Roman aqueduct, using the old natural sources of the Divor.[51]

So, against this background, it is not surprising that in the 16th century even André de Resende in Évora or Francisco de Holanda in Lisbon, took matters into their own hands to study and defend the old hydraulic works praising not only the antiquity and notability of their hometowns but also the political attitude of their royal sponsors. These two humanists were certainly not short of reliable historical bases to legitimize their commitment to such a great endeavor. In fact, we now know that the 'Sertorian' aqueduct of the capital of Alentejo, despite the unnecessary 'fabrication' of epigraphic proofs by Resende, preserved solid (albeit few) archaeological evidences from the Roman period and, on the other hand, that Holanda proved to be right in his many descriptions of old structures, like the one in the reasoning presented to King Sebastian in *Da Fábrica que falece ha* Çidade *de Lysboa* (1571) to 'restore' the Águas Livres (Free Waters) fountain used by the Romans to supply *Olisipo*.[52] On the other hand, the identification of the Belas Roman dam in the Águas Livres site (*fig. 3*) matches the correct evaluation of an archaeological structure that was suitable to reinforce this area's supply capacity and, furthermore, the perception that this capacity and height could indeed ensure a constant perennial flow that would make it possible to convey water to Lisbon using gravity. The young King Sebastian had no doubts about this possibility and in a letter from March 2nd 1573 was pleasantly informed of the efforts made by the council of Lisbon with regard to Águas Livres indicating how important it was to meet the city's demands and to decorate it, recommending the completion of everything that was required for the construction of that important work.[53]

These efforts by Francisco de Holanda were also reported by Inácio Barbosa Machado in the 18th century despite a wrong association with King Manuel. According to this author, it was acknowledged after several experiments that the water from the Andaluz area was not enough to supply a large fountain in Rossio square, so there was a decision to convey the famous and plentiful waters known as Águas Livres. The famous architect Francisco de Holanda was heard and following the orders of the Sovereign, designed the fountain through which these waters should flow. A representation of Lisbon was sculpted on top of a high and imperious column surrounded by four burly elephants as if four rivers flowed from their trunks into a majestic tank built with the finest and most polished marble in the Kingdom.[54] There are no doubts that Francisco de Holanda and King John III following the reconstruction of the Água da Prata Aqueduct in Évora which occurred between

1533 and 1537 when the king was living in the city were responsible for the first attempt to 'bring back' the water from Águas Livres to Lisbon, more specifically to Rossio square through the four elephants fountain that His Majesty intended to have built before his death; his brother, Prince Luis, said he wished that the water could reach the Ribeira quarter so that at least one of the elephants could supply the ships from India.[55]

Within the scope of these first attempts to bring water to Lisbon along the foundations of a Roman route, the council of Lisbon in an office record from September 11th, 1618, decided along with the agreement of the viceroy to bring the water from the Água Livres area to the city, as in the old days, along a route where traces of pipes were still being found, taking advantage of other springs that made the flow stronger and adding other springs that might be found along the way.[56] There was the need to proceed with analyses to the outflow of the springs which were usually conducted in September at the end of the summer, in order to clear any doubts regarding their abundance and quality. The information about the result of these analyses is also provided by the record of the letter that the senate of Lisbon sent to the king a few days later. It states that, after the many efforts made by the council to bring water to the city, as requested by the Sovereign, several council officers went twice with the Viceroy - the Marquis of Alenquer - to the Águas Livres spring and decided that, together with other springs, it was good and sufficient to be brought to the city and supply the required fountains.[57]

Curiously enough, Philip I of Portugal ordered the conduction of a practical test of the project involving the construction of wooden pipes, a quick solution to ensure that the construction was feasible before it was definitely built in stone however we do not know if this test was ever made.

During his short stay in the Portuguese capital, which occurred between June and September 1619, Philip II visited the ruins of the old Roman aqueduct and the dam with the aim of promoting its reconstruction or replacement,[58] a circumstance that if true, seems to agree with an exchange of correspondence between the Council of Lisbon and the king, whose epilogue was the arrival of Leonardo Turriano in the following year. Regarding the steps taken by this architect, we know that thanks to a letter sent to the court on September 24th, 1620 that he suggested four possible 'ways' (courses) to convey the Águas Livres's water to Lisbon while also explaining the corresponding topographic routes as well as the expected financial costs. The purpose was to convey the water to São Roque using as an intermediate reference point, the São Sebastião da Pedreira water mine which was surely an important aquifer in terms of supply. Four possible routes began at a site located close to the Benfica Road, as shown in a plan. A statement that suggests that up until that point, the route of the aqueduct raised no doubts (naturally because it was similar to the old one or followed it closely). After explaining three of the solutions, Turriano described the fourth one,which corresponded to the old Roman aqueduct that, for being 10 palms (ca 2.2 m) higher than the road, could supply the two urban sites, São Roque and Santo André Gate (*fig. 4*), as in the old days, because there would be enough water for both of them.[59]

Leonardo Turriano was quite renowned. He was one of the most gifted and respected architects in the Philippine court who is believed to be the author of several large and high-quality military and civil projects scattered across the vast territory of the Habsburgs, particularly in the Iberian Peninsula. So, the idea that he might have been wrong while considering a route and a given topography or even a specific height for the Roman aqueduct of Lisbon is not acceptable. In fact, we believe that Turriano knew the old route in its entirety considering the certainty with which he describes it, despite the fact that, unfortunately, there are no traces of the colored plans he drew for that purpose. The reference to the fact that the proposal that involved the 'caño uiejo' (old aqueduct) was the less favorable because it crossed many important properties from powerful people is a clear sign that, at least, the architect knew its outline, surely based on topographic calculations and on occasional traces found along the way.

Fig. 4. Santo André gate drawn ca 1910 by Roque Gameiro (1864-1935). The gate was demolished in June 1913 (source Lisboa Velha 1925, fig. 64).

Already in 1617, the architect Pedro Nunes Tinoco, who had also been asked to take part in the team that should design the Lisbon water supply system, had already mentioned the antique nature of the Águas Livres springs.[60] There he found the Belas Roman dam, a structure that was believed to have been built by the Moors to dam up the river's water and create a lake.[61] But, at a later stage of the project, and while analyzing the structure of the old pipe, the architect states that it was an ancient Roman construction and, with regard to stake 39, which was 13 869 palms (ca 3.1 km) downstream Águas Livres, he mentioned the top of the quarry under which the ancient pipe goes.[62] This is a curious reference that might explain the expression used by Francisco de Holanda when he urged King Sebastian to convey the water from the Águas Livres spring which had been used by the Romans to be bring water two leagues (ca 10 km) to Lisbon via underground pipes, something that implied drilling through many hills, involving many costs and a lot of work.[63]

While Francisco de Holanda, Leonardo Turriano and Pedro Nunes Tinoco all agreed with the possibility of bringing water to Lisbon via the topographic route of the Roman aqueduct from Águas Livres, identifying, for that purpose, a series of old structural traces with some directional consistency, Manuel da Maia was one of the engineers asked to take part in the construction of the Lisbon aqueduct, promoted by King John V. In his notes on the water supply to Bairro Alto, he recorded that in August 1728, two sections of water pipes from a previous attempt had been found in a place known as *alveo* at approximately eleven thousand, seven hundred and eighty palms (ca 2.6 km) downstream of the main spring of Águas Livres spring.[64]

Finally, from a whole sequence of remarks made by qualified architects that were faced with Lisbon's hydraulic issues, we should highlight the article by Miranda Montenegro on the 'Old Lisbon Aqueduct', published in 1896.[65] He states that the traces of old structures found in wells, stairs and galleries on Retrozeiros, Prata and Madalena streets, as well as along the 18th-century Águas Livres route (in Porcalhota, Almarjão and Rascoeira), together with the analysis of the composition of the cement found in these ruins, led him to believe that in ancient days, there was an aqueduct used to convey some of the water from springs located in northern areas higher than the city to Lisbon; on the other hand, the engineer Carlos Ribeiro, in a 1879 report,[66] mentioned that he found traces of an aqueduct that seemed parallel to the 18th-century one but was built 2 or 3 meters below it; some sections of wall and pipes built with mortar and tile fragments using a Roman technique were located close to the Príncipe (or Almarajão) gate and to Rascoeira.

Despite the fact that all these authors corroborate the archaeological evidence of the existence of a Roman supply system in Lisbon and under part of the current route of the 18th century Águas Livres Aqueduct between its source in Belas and at least the Rascoeira-Porcalhota area (currently known as Amadora), the truth is that between this area and São Roque and Santo André Gate, nothing concrete has been found as of yet, meaning that the idea of the *Olisipo* aqueduct is (still) an open possibility. It is so vague that many authors have been avoiding the issue with an awkward silence. But, is the lack of material evidence reason enough for us to doubt the authenticity of such forceful literary records? In fact, while the legitimate argument that the lack of archaeological evidence can curtail a categorical statement on the subject, the truth is that what we know about the Roman urban design of cities with a similar size and status,[67] what we know of the aqueducts's topographic feasibility of the orientation of the known archaeological structures or of the water needs of *Olisipo*'s thermal complex which we have already mentioned, seems sufficient to justify the existence of a Roman hydraulic structure to connect the Águas Livres springs to the heart of the city of *Olisipo*.[68]

In favor of the thesis we are advocating, we should also highlight the research conducted by João Carlos Viegas and António Gonzalez on the Roman Amadora aqueduct (*fig. 5*), particularly two findings of their field work: the estimated volume of water retained by the Belas dam in the Carenque stream's valley (125,000 m^3, according to Almeida 1969) and the maximum flow rate, estimated at 6,400 m^3/day, which allowed the authors to suggest that the aqueduct supplied an important human settlement (*fig. 6*).[69] We should also mention the idea that the Roman aqueduct studied by Viegas and Gonzalez was apparently roofless (hence their suggestion that it might have served agricultural purposes); despite the fact that it is not a very likely circumstance, considering other known similar cases, it does not exclude the possibility that it might have been used to ensure the public supply of a city as large as *Olisipo*. On the contrary, it strengthens the key aspect of our proposal: the idea that the perennial flows from Águas Livres springs and other sources located along the route were preferentially used to supply the various known public and private thermal baths.

Fig. 5. Section of the Roman aqueduct (commonly called as Amadora aqueduct), in Gargantada zone, ca 700 m south of Carenque (photo José Manuel de Mascarenhas).

Fig. 6. Aspect of another section of the commonly called Amadora aqueduct, in Gargantada zone (photo José Manuel de Mascarenhas).

Geographic Modelling for the Generation of an Optimal Route

The Digital Elevation Model

The definition of a modeling base is largely dependent on the characteristics of the available spatial data considered valid for the modeling process.

The time-related constraints associated with the evolution of the physiographic characteristics cannot be entirely eliminated considering that, together with the natural morphological evolution resulting from geological morphogenesis and erosion/deposition processes that might have occurred, there were probably changes of anthropic origin that are very difficult to identify and represent. So, the representation of the land takes on an essentially structural perspective and is based on the creation of a digital elevation model considering altimetry data obtained with a resolution suited to medium/large scales within the national context, such as altimetry mapping at a 1:25,000 scale. The use of larger scales would naturally allow proceeding with a greater accuracy, but would simultaneously be more likely to reflect changes of anthropic origin or other morphogenetic factors. Figure 7 shows the digital elevation model in a matrix format based on altimetry information on a 1:25,000 scale with an equidistance of 10 meters between contour lines.

The chosen interpolation method[70] uses an approximation based on an iterative interpolation technique[71] which allows estimating values from a recurrent contextual perspective and an adaptive multi-resolution process. Using information bases with relatively low altimetry observation frequencies it is possible to obtain a more appropriate estimate of the terrain's 'functional' behavior.

Creation of a Conditioning and Feasibility Surface for the Construction of the Aqueduct

The creation of a conditioning surface is based on the definition of a uniform descent scenario considering the slope values mentioned in the literature about the construction of Roman aqueducts. Several uniform descent surfaces were derived generating, via a reversal of the formula used for calculating the slope, a fictional altitude being a function of the Euclidean distance to the identified points of destination (Santo André Gate and São Roque).[72] The surface chosen as reference was the one that allowed maintaining an average uniform slope of 0.15%.[73]

In order to create a cost surface based on the assessment of the distance to the constraint surface, we generated a surface that resulted from the subtraction of the real height from the values of the constraint surface. In this way, we were also able to create a scenario of impossible gravity drainage, eliminating from the subsequent analytical procedures the entire area classified as such.

Creation of the Differential Cost Surface and Calculation of Optimal Routes

For the viability area that was identified, a constant descent surface was generated considering the heights of the initial point (Gargantada) of a control test point[74] and of the potentially final points (Santo André Gate and São Roque). An interpolation based on the *inverse distance weighted* method, with a unit linear valuation of the above mentioned points was used. The creation of a differential cost surface results from the absolute value of the difference between the constant descent surface and the real hypsometric values, which provides an effective constraint for the definition of the *Cost-Distance* and the *Cost Back Link* surfaces that are required to generate the optimal routes between origin and destination points (*fig. 8*).

The spatial definition of optimal routes considering the origin (eastern aqueduct archaeological remain in Gargantada site), the control test point and the potential destinations (Santo André Gate and S. Roque) is illustrated in figure 9.

The generation of the optimal route is based on the *Cost Direction layer* (and inherently on the *Cost Distance layer*) which defines on a cell by cell basis, the optimal crossing route from the destination cell-points to the original cell-point. The optimal layout for the aqueduct route thus obtained is converted from the raster to a vectorial shape file for better representation and cartographic manipulation (*fig. 10*). The comparison between the optimal route and the constraint structure reveals a high adherence of probability in the terrain, as well as by the almost virtual absence of positive differentials - locations with possible increases in altitude, which would suggest the need for the construction of devices, such as trenches and tunnels, to maintain the negative differential required for water drainage.[75]

Conclusion

In the daily life of *Olisipo*, water - from the gurgling fountain that quenched the citizens' thirst, to the flows that supply the *balnea* and support the powerful *garum* industry, to the sources of purifying waters[76] - played an unquestionably crucial role. The current state of the knowledge on the urban occupation of the city allows attesting that

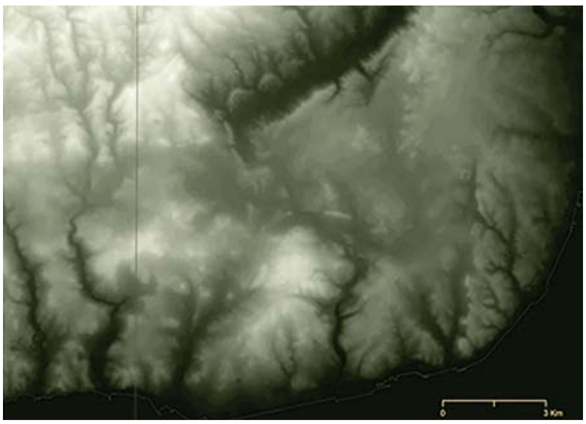

Fig. 7. Digital elevation model for valid area (after N. Sousa. Neves).

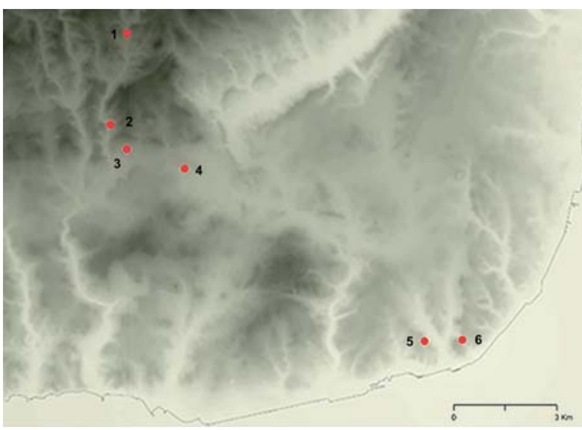

Fig. 8. Differential cost plane: 1 Águas Livres *springs and dam; 2-3 Limits of section with aqueduct archaeological remains; 4 Control test-point in Benfica old road; 5 São Roque site; 6 Santo André gate (after Nuno Sousa Neves).*

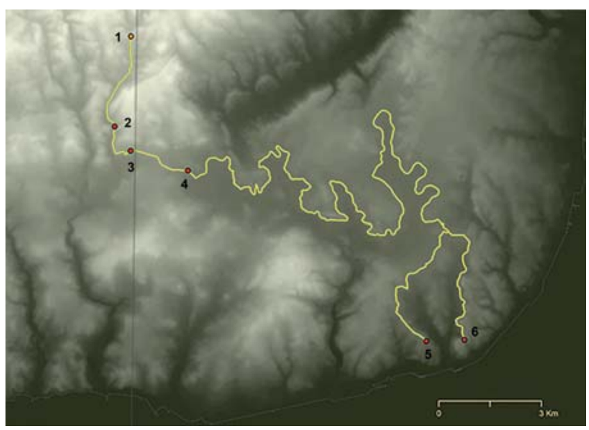

Fig. 9. Potential aqueduct route: 1 Águas Livres *springs and dam; 2-3 Limits of section with aqueduct archaeological remains; 4 Control test-point in Benfica old road; 5 São Roque site; 6 Santo André gate (after Nuno Sousa Neves).*

Fig. 10. Potential aqueduct route on 2016 Digital Globe / Google Earth satellite image: 1 Águas Livres *springs and dam; 2-3 Sector with aqueduct archaeological remains; 4 Control test-point in Benfica old road; 5 São Roque site; 6 Santo André gate (after Nuno Sousa Neves).*

there were structures that required a constant supply of running water. Among these, we should highlight three thermal complexes that have already been reliably identified and, on their own, involved the use of a significant amount of water, leading us to consider that the city was very likely supplied by one or more aqueducts. This issue has been a topic of discussion since the Renaissance and authors like Francisco de Holanda, Leonardo Turriano and others, believed that it was very likely that the Romans had built an aqueduct for *Olisipo* using the Águas Livres springs and dam. Despite the fact that a section of a Roman aqueduct coming from that area has been identified between Carenque and Amadora, there have long been doubts about the possibility that it might have belonged to a much larger structure intended to supply the Roman Lisbon.

We decided to actively contribute to the debate by analyzing the viability of that Project based on topographic information (meso-scale) and by creating a geographic model using a Geographic Information System (GIS).

The results are deemed very promising given that, considering an average slope close to the one used in Rome and other locations, it was possible to define routes for the two different *termini* referred by Leonardo Turriano: the Santo André Gate and São Roque site.

We also defined the cartographical limits of sites were there might have been the need to overcome small barriers via the construction of small devices (such as trenches or tunnels) or, alternatively, via a local increase in the route's sinuosity.

In addition to the limitations associated with the method, there are other constraints that call for a certain caution in the interpretation of the results. Despite the fact that we used a topographic base with a relatively small scale in order to reduce, as much as possible, the 'noise' related to anthropic interventions carried out throughout history, these surely existed and took on a greater significance mainly following major earthquakes (particularly the one occurred in 1755), or once there were technological means that allowed making important changes in topography, something that, in the region, occurred mainly after the 1930s, together with an urban sprawl and the construction of major infrastructures. On the other hand, considering that there are already numerous studies on the way how the Romans took advantage of the territory to build aqueducts, being supported mainly by empirical information, and precisely for that fact, the final design of the construction might not have corresponded to an almost 'ideal' design such as the one obtained via the use of a sophisticated computer model. Comparing the design obtained via the application of the computer model with the information provided by ancient authors, particularly Leonardo Turriano, we are aware that the choice made by the Romans was partly different and took advantage of areas with dominant inclinations,[77] avoiding the 'low' areas of Sete-Rios and Palhavã. Turriano also proposed solutions that crossed these areas, but considered them as choices different from the one made by the Romans.[78]

In short, based on Leonardo Turriano's description, the route of the *Olisipo* aqueduct was analysed using topographic information and geographic modelling by GIS proving to be viable. The optimal route that was generated might have been shortened by the Romans, namely by boring or trenching hillocks, or by building low walls to cross flat valleys[79] but no remains of such structures have been found yet. The usefulness of the application of this type of computer model is still rather clear when it comes to recognizing the hydraulic archaeological heritage, allowing us to obtain increasingly 'tuned' solutions or find answers regarding the viability of specific constructions.

Notes

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1 Calado 2008 quoted from Banha da Silva 2011, 203.
2 Guardado da Silva 2010, 33.
3 Strab. 3.3.1.
4 Banha da Silva 2011, 204.
5 Plin. *NH* 4.117 quoted from Mantas 1990, 161.
6 Mantas (1993) quoted from Guardado da Silva 2010, 38.
7 Banha da Silva 2005, 19.
8 Banha da Silva 2011, 205.
9 Banha da Silva 2011, 204.
10 Largo da Madalena, according to Alarcão 1994, 58-63; see also Cardim Ribeiro 1994, 75-95. The location of the forum is controversial and there are proposals for other locations (see Fabião 2010, 343-359).
11 Banha da Silva 2011, 205.
12 Banha da Silva 2005, 30.
13 Cardim Ribeiro 1994, 83-85; Fabião 2010, 354. There was probably a second forum, as in *Ostia* and *Hispalis* (Seville).
14 Mantas 1997, 30.
15 Pimenta 2004 quoted from Banha da Silva 2005, 20-21. The area occupied by the Late-Empire *Olisipo* (*pomerium*) was probably smaller than it is usually considered to be. Banha da Silva 2011, 204 considers the possibility that this recession might have been the result of the instability experienced during the Civil Wars.
16 Banha da Silva 2011, 205.
17 Banha da Silva 2011, 206.
18 Mantas 1997, 34.
19 Guardado da Silva 2010, 51.
20 Alarcão 2005, quoted from Fabião 2010, 352.
21 We highlight the Cassian Baths and the so-called Augustales Baths.
22 With regard to these small thermal baths, see Filipe/Calado 2007, 1-12. The authors mention that it is not clear whether these facilities were public or private.
23 It occupied an area equivalent to that of two 18th century AD blocks of houses.
24 Encarnação 2009, 481-493. See also Fernandes 2009, 191-207.
25 Fernandes 2009, 199.
26 Thomaz Caetano de Bem, Biblioteca Nacional de Portugal, Cod. 104, Fl. 8v. e 9.
27 Banha da Silva, 2011, 208.
28 Banha da Silva, 2011, 208.
29 This assumption is supported by the fact that all the known springs of *Olisipo*'s hill are located at its foot. On this subject, see Moitinho de Almeida 1985, Pais et al. 2006, and Ramalho/Lourenço 2005.
30 Filipe/Calado 2007, 9.
31 Filipe/Calado 2007, 6 and 9.
32 Vieira da Silva, 1987, 148. Furthermore, this author mentions (152) that King Afonso V donated a thermal complex located close to the fountain and the wall in 1468. Were they from an earlier period? It would not be surprising to find thermal complexes in this area of the city in the Roman period (Filipe/Calado 2007, 9.).
33 Fish sauces (*garum*) and fish brine.
34 Bugalhão 2001, 175.
35 Bugalhão 2001, 62.
36 Bugalhão 2001, 66. One of the tanks was square and had a drainage system, something that was not found in the other, semi-circular, tanks.
37 The most likely hypotheses.

[38] Fabião 1994a, 147-162.
[39] Fabião 2010, 343-359.
[40] Fabião 2010, 354.
[41] Fabião 1994b, 67-69. The possible existence of a corporative *forum* in that area is currently supported by most specialists; however, this subject is still open for discussion.
[42] Mantas, 1990, 149-205.
[43] It was located on the corner of Prata Street and S. Julião Street. Those waters gave a reputation to the chapel of Nossa Senhora da Oliveira located nearby until being destroyed by the 1755 earthquake (Guardado da Silva, 2010, 45).
[44] Banha da Silva 2011, 204 - 205.
[45] Vale/Santos 2003, 177-186. The archaeological excavations revealed a structure that corresponded to a section of the *euripus* and the arena.
[46] Vale and Santos consider that it needed to be supplied by the aqueduct (Vale/Santos 2003, 181). We only find it necessary for the aforementioned reasons. If the fountains did not exist, there would not have been the need to ensure a constant water flow.
[47] Alexandra Gaspar e Ana Gomes (2007) quoted from Banha da Silva 2011, 208.
[48] Pereira 1885, 530-532.
[49] As we can see in the expression *Ebura Colonia Romana*, in the illumination included in the *foral novo* (new charter) of the city, dated September 1st, 1501.
[50] Gomez de Somorrosto 1820.
[51] Bilou 2010.
[52] Holanda 1970, 99-102.
[53] Freire de Oliveira 1885, 549.
[54] Barbosa Machado 1745, fl.126.
[55] Holanda 1970, 100.
[56] Freire de Oliveira 1887, 416-423.
[57] Freire de Oliveira 1887, 421.
[58] Almeida 1969, 179-189.
[59] Freire de Oliveira 1885, 573-574.
[60] See, for example, Portugal Biblioteca Nacional 2001, 91.
[61] Viegas/Gonzalez 1997, 3.
[62] Viegas/Gonzalez 1997, 3.
[63] Holanda 1970, 101.
[64] These included blocks of well-prepared lime mortar with small stones or coarse gravel, which was three and a half palms wide and four palms high and, in the upper section, a gutter that was one palm wide and one palm high, which could fit 13¾ pipe bracelets, corresponding to a total of 200 rings; furthermore, that gutter had a thin layer of lime with fine stone and brick gravel and certainly also stone dust also; a section of that gutter was kept for observation. It was much softer than any type of masonry works. A glazed tile was also kept; there were water residues deposited on it, 1/6 palm layer, and the union was as resistant as that of any marble (Viegas/Gonzalez 1997, 4).
[65] *APort* 2/10-11, 1896, 229.
[66] *Revista das Obras Publicas*, October 1879.
[67] Even considering the latest interpretations of the modest size of *Olisipo*'s urban mesh, which relativize its role as an attractive maritime *polis*, an argument that is actually contradicted by the monumentality of the known structures. See Banha da Silva 2011, 203-212.
[68] By analyzing a detailed topographic plan of the Castelo Hill, shown in Banha da Silva 2005, fig. 2, we can see that the upper limit of the area occupied by the Cassian Baths is located at a slightly lower height than that of the top of the Santo André Gate, suggesting the possibility that these Baths might have easily been supplied by an aqueduct whose route passed over that Gate.
[69] Viegas/Gonzalez 1997, 12.
[70] Developed by Hutchinson 1996.
[71] Known as *iterative finite diference interpolation technique*. See Wahba 1990.
[72] In this study, we chose as starting point for the aqueduct a location in the Gargantada area (ca 700 m to the south of Carenque) where the structures of the Roman Amadora aqueduct are clearly visible. More specifically, this point concerns the eastern extremity of the known Roman remains (*figs 7-10, point 3*).
[73] This slope corresponds to the average slope of most of the aqueducts of Rome, as mentioned in Nordon 1991, 48.
[74] This control test-point is located in Amadora (Porcalhota zone) quite close to Benfica road and in theory is 10 palms (ca 2.2 m) higher than the road according to Turriano (see *figs 7-10, point 4*).
[75] Only in one site, close to Fonte Luminosa (Alameda Dom Afonso Henriques), a hillock should have been necessarily overcome through the opening of a small tunnel or trench.
[76] Caetano 2008, 220-222.
[77] According to Turriano, the Roman aqueduct was ten palms (ca 2.2 m) higher than the Benfica road.
[78] The routes he called two and three. See Turriano 1990, 180.
[79] There is a very flat valley, easy to cross using a low wall, in the area of the old Quintas (Farms) of Poche (José Alvalade Stadium), Mouras and Cabanas, according to the topography shown in Silva Pinto/ Sá Correia 1906.

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