Hydraulic Study of the Water Supply to the City of Seville through Its Aqueduct between the 17th and 19th Centuries

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Abstract. The aqueduct of the Caños de Carmona was in operation from 1172 until its demolition in 1912. Its infrastructure was an essential resource to supply water to the city of Seville. This study attempts to analyse the supply and distribution system used in the city in the Modern Age. The research is focused mainly on obtaining water from the Santa Lucia spring to 19 km in Alcalá de Guadaira, its route through the aqueduct, the division for the distribution between different users in the general partition ark and its subsequent distribution to the final destinations. This study aims to develop a hypothesis about the principles of water distribution through the city and to estimate the percentage of water going to each client based on the theoretical concession that should reach each home.

1. Introduction

The purpose of this article is to understand the system that supplied water to the city of Seville through its aqueduct. To this end, the following main objectives have been set: First, to propose a hypothesis of the operation of the hydraulic infrastructure during this time and to determine the theoretical flow of water to the city by the aqueduct. Second, to understand how the distribution and different modifications during the last three centuries were interpreted and to accurately draw the plan and elevation of the reservoir from the only known graphic source, a plan found in the historical archive of the municipal water company of Seville (EMASESA), taking into account that these distributions were modified due to the sale or barter of the concession made by the king. Finally, to estimate the theoretical flow of water that should reach users based on the dimensions of the pipes with calculations using the unit of measurements of the “Castilian inch” and the "water straw".

This investigation began with a review of the bibliography to determine the state of the current research on the aqueduct. This information was used to conduct a critical study on the different published hypotheses on how the water reached the distribution arch and statistical data about the water capacity from the 17th to 19th centuries. Plans at the scale of the aqueduct have been developed from graphic, archaeological, documentary and literary sources. Furthermore, topographic work has been executed to analyse the remaining canal material of the canal and to establish the geographical coordinates of the references, the exact locations of the sections of the aqueduct that are still standing and to determine the hydraulic quota above sea level. Using this information, the planimetric survey of the longitudinal profiles was performed to determine the how the water of the aqueduct of Seville
arrived in the ark and was sent to its destination for different users. The water was moved and distributed by gravity, reaching a distribution extend of more than 2 km.

### 2. State of the matter

The water supply of the city of Seville through the aqueduct of Roman origin and Islamic use has been a permanent object of historical research; many authors have mentioned the aqueduct, Carmona Gate and the ark of distribution in their writings. However, little research has been done from an archaeological point of view and even less from a hydraulic standpoint. There are no studies that have analysed, in depth, the supply system, existing graphic sources, or the Sevillian material hydraulic heritage. Considering recent studies performed in the past fifty years, Fernández Casado's [1], the doctoral thesis of Granero Martin [2] and Jimenez Martin [3] have studied the aqueduct. The doctoral thesis of Antonio Albardonedo included the supply to the city [4]. However, Manuel Fernandez Chaves, in his doctoral thesis, studied from a historical point of view the municipal administration of the water supply in modern Seville, focusing on the Caños de Carmona [5]. Among the remains of the old water supply of Seville, there are three sections of the aqueduct in different parts of the city. The closest area to the missing Carmona Gate and to the distribution ark are the stretches that comprise Florida Street ‘figure 1’ and Luis Montoto Avenue ‘figure 2’, and two kilometres to the east, the section known as Los Pajaritos ‘figure 3’, alluding to the neighbourhood where it is located. Remains of the pipe that connected the ark to the Real Alcazar remain embedded in the Islamic wall of the city, in the Murillo Gardens and the Alley of the Water.

3. **Historical considerations**

Many researchers have discussed the Roman or Muslim origin of the aqueduct. Although the majority of the construction of the aqueduct was completed in Muslim times, the execution of the underground mine and the encounter with the great water spring are attributed to the Romans. These facts are clarified by Ibn Sahib Al Sala. The narrations of the 20th century Hispano-Muslim historian stated that, following the construction of the Buhayra Palace, while looking for a water supply, workers followed the tracks of a Roman gutter and the traces of an ancient aqueduct took them to the spring. Once discovered, the governor Almohad Abu Yaqub Yusuf in 1772 ordered to transport the spring water to the interior of Seville [6].

This Roman-Muslim construction has been described and exalted throughout its history. The route began with the capture of water from the spring of Santa Lucía, which is currently located on the property of Los Cercadillos (Alcalá de Guadaira) [7]. From this aquifer, the Zacatin (another important emissary of water) goes off towards the spring in the direction of the city of Seville, crossing various underground galleries. In the past twenty years, the main investigators of the underground galleries have been the speleological society GEOS [8], Romero Gutierrez [9] and Garcia Rivero [7]. Approximately two and a half kilometres from the spring, below the Gutierrez de Alba Theatre, is the underground mill of the mine. This engineering work, which can be accessed by a ramp near the theatre, was distributed on two levels. The mill was on the upper level, and the underground mine ran three metres below [9]. The main gallery going towards Seville came to light in the Hacienda of La Red del Agua. The high impact produced by the construction of an industrial estate makes it difficult
to determine the exact location of the vents of the aqueduct. It is known that the vents were located beyond the property of La Red because of the State official newsletter ‘Gaceta de Madrid’, which in 1846 called it ‘el Salto del Lobo’ [10]. Upon reaching this point, the route of the aqueduct diverted to the right, providing a new water supply to the flour mills of the time. The most modern map that showing the location of the mills is General Rafael Lacaze’s from 1869 [11]. After reaching the mills, the route ended in the area where the small temple of La Cruz del Campo is located. In this place, the Almohads built a large arcade heading for the city of Seville. This section follows an almost straight line through the current Luis Montoto Street, in that time called Carmona, hence the name of the aqueduct. This was the final stretch, near present-day Florida site, where the aqueduct reached its highest elevation at the crossing of the Tagarete River, forming a bridge aqueduct with a three-tier archway. Finally, the aqueduct ended at the Carmona Gate, where it was the ark of distribution of water of the city.

The city was very different in the 19th century. Because part of the water supply route was through flour mills across a surface ditch, the water quality continually worsened. Such was the need to obtain better quality water that the city had to rethink the system of supply, and in 1819, the assistant Arjona advised taking advantage of the existing infrastructure. The idea was to construct a new section of aqueduct to replace the superficial route of the mills, replacing the nine sections that were still standing. In 1825, a report on the viability was sent to Madrid, and it was not until November 1827 that the Royal Order arrived granting approval to the project [12]. The project to save three kilometres by joining the beginning of the new section from the Net to the Cruz del Campo was completed by the architect Melchor Cano. Work began in 1828 [13] but was stopped in 1833. By April 1842, “7.158 5/6 sticks of aqueduct had been built, still missing 1.600 sticks” [10], that is, 20% of the construction was incomplete. The work was resumed in 1846 by the architect Gabriel Gómez Herrador, who proposed a new project for the definitive construction of the aqueduct, which included 110 arches [13]. In 1871, the aqueduct construction was ended [14]. Of the existing remains, the section that best represent these works is the branch in the neighbourhood of Los Pajaritos.

4. Hydraulic study of water supply in the city
4.1 Calculation of the theoretical water flow that came to Seville through the aqueduct

The flow of water carried by the aqueduct and received at the ark of distribution depended to a large extent on the capacity of the source of Santa Lucía. Undoubtedly, the flow of water varied over time. To this day, the flow of the spring is an inexhaustible source that provides approximately 20-30 l/s [15]. To obtain approximate data about the historical water flow of the aqueduct, it is necessary to consider the characteristics of the infrastructures that carried it. Because it is not possible to perform an in situ flow test, the only possibility is to perform an approximate mathematical calculation using the formula \( Q = V \times S \), where \( V \) is the flow velocity and \( S \) is the transverse hydraulic section considering a constant spring flow. In past decades, other authors have calculated the water flow of the aqueduct using the formulation of Dupuit [2]. In this case, to calculate the speed, the formula of Manning-Strickler (1) is applied.

\[
V = KR^{n/3} \frac{1}{n+2} \tag{1}
\]

\( K \) (Manning roughness coefficient) is 22 since the specum material is considered to be a rough and irregular channel. To determine \( R_h \), the wet hydraulic radius, the section must be considered. It is not known which portion of the specum was wet, so a margin of 75% of the wet height is used. Field work has shown that the section is not uniform throughout the route due to the remodelling that has been performed and to the calcareous concretions that have adhered to the surface. Therefore, it is estimated that the best position is an average of the three existing sections. The middle section is 1.00 x 0.50 m. It would be natural to have a trapezoidal section of the specum since it would decrease the velocity of the flow [2], but this is not the case for this aqueduct. To determine the slope, in situ reconnaissance work of the remains was performed via a planimetric survey and topographic investigation. The field work has identified the georeferenced location of each element of interest through the base mapping of
the 1:10000 scale maps of the province of Seville obtained from the network of the Environmental Information of Andalusia and the quota on the level from sea [16]. From the completed research, the slopes of the remaining sections are calculated. The data show that the slopes are different because they have suffered numerous restorations throughout history (the last one in 2009), so these values are unreliable. The best option, therefore, is to use the La Florida section due to its proximity to the distribution ark and because the flow of water in this section should not have any additional leads before reaching the deposit ‘figure 4’.

![Figure 4. Calculation of the slope and hypothesis of the last course of the aqueduct.](image)

After selecting the section, the sea level of the water sheet is checked. The difference in the extremes indicates an incline of 0.05 m. Taking into account these data and the length, the slope is 2.187 % (a fairly acceptable slope for this type of aqueduct). With the data analysed above, a survey is conducted and the total theoretical flow rate of the channel is calculated (table 1). Taking into account that the recommended water circulation velocity (to avoid erosion or sedimentation deposits) oscillates around 0.5 metres/second in Roman aqueducts [2], the data indicate that the channel had a slow speed.

| Height of the water sheet (m) | Hydraulic section (m³) | Hydraulic radius (m) | Length (m) | Slope (m) | Average slope (m/m) | Manning roughness coefficient (K) | Speed (m/s) | Flow rate (m³ / day) |
|------------------------------|------------------------|----------------------|------------|-----------|---------------------|-------------------------------|------------|---------------------|
| 0.75                         | 0.38                   | 0.15                 | 22.86      | 0.005     | 0.00218             | 22                            | 0.30       | 9,411.14            |

4.2 The ark of water distribution to the city

The ark of distribution was at the Carmona Gate. The door was located to the east of the city and comprised the walled medieval enclosure. It was one of the most important entrances and was recognized for being the place where the aqueduct arrived. The canal entered the town by passing above the wall to connect with the main water distribution ark. There is no record of what year the deposit was built. During the reign of Abu Yaqub Yusuf, there was another water reservoir in the historic centre of the city, near the Calle Mayor, according to Ibn Sahid Al Sala [6]. It is believed that this original deposit could be the one that has recently been excavated in the Plaza de la Pescaderia [17]. Subsequently, there was a substantial alteration in the water storage system that changed the location of the distribution arcade or castellum, but there is no record of the exact date of the construction of the new general distribution ark being studied in this work, although several hypotheses have been proposed [18].

To determine how delivery was achieved by the distribution ark, the plans and the historical bibliography have been investigated. Concerning the graphic representations, two blueprints of the ark have been found. The first is a sketch from 1618 owned by the Historical Archive of the Cathedral [19], which shows six auxiliary boxes with the following public or private destinations: La Macarena, San Lorenzo, Duke of Medina Sidonia, San Francisco, El Salvador and a sixth name that is not recognized. The second is owned by the public water company EMASESA [20]. Nothing is known about the authorship nor year in which the drawings were made. According to comments from the company’s own technicians, they suspect that it is a copy made in the 19th century and that there is another copy at the Municipal Archive. More copies of this blueprint have been sought, but they have not been found. This plan could be from the 17th century since, as will be seen later, there is a report from an identified file of the Municipal Archive of Seville that speaks of the ark distribution canals.
and that matches exactly with those shown in the plan from 1655. Regardless, the drawing is useful for this investigation because, in addition to being delineated with some rigor, the size of the exit canals to the different public and proprietary destinations is described in the text ‘figure 5’.

![Figure 5. Drawing in plant and elevation of the distribution ark [20].](image)

In the distribution ark, the water from the pipes was decanted and distributed. The water was divided into seven smaller auxiliary chests corresponding to the different distribution canals and conduits leading to the final destinations. At the bottom of each auxiliary box, there was a sheet of bronze with its corresponding ‘wounds’; that is to say, calibrated holes that the water passed through. From there, the water was distributed by gravity to the public sources of the city and to clients who had received a concession from the king or a water grant. Additional, two other canals embedded in the upper part of the wall were directed towards the Real Alcazar. The pipe in the Real Alcazar had no secondary casing, and the water outlet was at a lower level than the others. This meant that the distribution first covered the needs of the Royal Palace, and when there was an adequate water supply, it was distributed equally to the remaining customers. The ark was cleaned and maintained by the Real Alcazar and, as it was located inside a locked door, it was one of the parts of the system that was not affected by the frauds of men [18].

4.3 Study of the theoretical flow of water to customers

The general system used to supply Seville through the aqueduct used gravity. Most of the pipes leaving the reservoir used gravity to transport water to the water boxes placed throughout the city, which distributed the water to fountains, public buildings and privileged users. The recorded historical documents confirm that the water straw was used to measure the flow of water to different users. The water straw was a frequently used unit of measure in the Modern Age, although its value differed by city and territory [21]. The historical documents of the Municipal Archive and those cited by various authors show that it is not easy to determine the exact number of water straws that each pipe carried. Furthermore, it is difficult to specify the actual flow because there is a discrepancy between the amount of water that each user was authorized to receive and what was actually received, not only because of the bad state of the plumbing but because there were robberies and thefts during its journey. Therefore, to calculate the water flow rate and the theoretical distribution percentages among users, this study is based on the explanatory text of the EMASESA plan, where the dimensions of each ‘wound’ (or hole) are recorded in Castillian inch or water straw.

A similar situation occurs for the determination of the hydraulic section of the water straw in the Modern Age. The Municipal Archive has the plans of Sebastian de Ruesta, dated 1657 [22], that different researchers have used to give their interpretations [23], and there is a bronze metre with
different diameters to measure the holes [24]. However, a report written by González y García de Meneses in 1889 is interesting. This report was requested by the City Council itself, which created a municipal commission of engineers and architects to establish the equivalence between water straw and the cubic metre. In this document, they conclude that the area of a water straw hole is 0.299 cm²; therefore, the diameter is 6.2 millimetres [25]. It is necessary to explain that several authors disagree with the results obtained by this commission [26]; they even determine a different equivalence for the water flow [14]. However, it is the best testimonial data that exists, and it serves as a tool to analyse and calculate the theoretical water flow according to the size of the hole in water straw units.

As discussed previously, most pipes transported water by gravity. Calculating the exact flow rate is not feasible since it is not possible to determine the water arrival rate to the initial boxes because they have been destroyed. However, as it is interesting to have an approximate calculation of the flow of each user to calculate their percentage of the supply, this research uses the formulation of Darcy (2) to determine the water flow under forced driving and Colebrook-White (3) to calculate the friction factor (coefficient of friction). Since it is not possible to determine the loss of load in each route, a constant loss of load of 2 metres is established, except in the pipe of the Real Alcazar, for which, due to the remains of the channelling inside the Islamic wall, it was possible to obtain the slope.

\[
\Delta P_{\text{friction}} = \frac{fLQ^2}{2gD} \cdot L \\
\frac{1}{\sqrt{f}} = -2 \cdot \log \left( \frac{k}{\sqrt{\frac{2.51}{4Q^2}}} \right)
\]

Table 2: Calculation of the maximum theoretical water flow to customers based on the EMASESA plan

| Branch - Customer                      | Number of holes | Inch / Water Straws | Diameter (m) | Water Flow m³/day | Distribution % |
|----------------------------------------|-----------------|---------------------|-------------|------------------|----------------|
| Real Alcazar                           | 1               | 14                  | 0.33        | 4,075.57         | 33.16          |
| Medina Sidonia                         | 6               | 107                 | 0.08 - 0.22 | 2,583.45         | 21.02          |
| Pilas Publicas (de la Ciudad)          | 3               | 84                  | 0.15 - 0.19 | 2,204.47         | 17.94          |
| Baños de San Juan de la Palma          | 2               | 39                  | 0.10 - 0.14 | 824.41           | 6.71           |
| Colegial del Salvador                  | 5               | 65                  | 0.07 - 0.09 | 776.79           | 6.32           |
| Duque de Medina Celi                   | 1               | 18                  | 0.11        | 654.81           | 5.33           |
| San Pablo                             | 2               | 39                  | 0.11 - 0.13 | 594.94           | 4.84           |
| Barca Rota                            | 1               | 23                  | 0.14        | 575.05           | 4.68           |

| Total                                  |                 |                     |             |                  | 12,289.50       |

It is necessary to clarify that the calculations have been made individually according to the number of ‘wounds’ (or holes) that appear in the plan and that, subsequently, they have been added according to the Branch-Client. However, in the plan, the diameter of the pipe for the Real Alcazar appears as 14 Castilian inches and not in water straws, which is why the conversion to metres has been made (one Castilian inch is 0.02322 m). The maximum possible theoretical flow (table 2) and the percentages of water going through each branch ‘figure 6’ were obtained.
4.4 Evolution of the distribution system to the different users

This study is based on the EMASESA property plan as it is currently the most accurate plan showing how water was distributed to different customers. However, in the abovementioned report, there is a table showing the distribution of the ark at different times [27] (table 3). These data are interesting because they indicate an evolution in the real concessions of water in the 15th, 17th and 19th centuries, indicating that the ark had to be rectified on at least two occasions.

Table 3. Table of the division of the water arriving at the city by the aqueduct and its distribution according to report of the engineer González y García de Meneses

| 15th century                  | 17th century                  | 19th century                  |
|-------------------------------|-------------------------------|-------------------------------|
| Huerta de Venacojal           | Alcazar                       | Macarena                     |
| Carrera del Alcazar           | Barca-Rota                    | Barca Rota (Navarros)         |
| Casa y fuentes de la Villa    | Colegial del Salvador         | Santa Paula                  |
|                               | De la Ciudad [28]             | Alcazar                      |
|                               | San Pablo                     | Cristina                     |
|                               | MedinaSidonia                 | Madre de Dios                |
|                               | San Juan de Palma             | San Pablo                    |
|                               | Medina Celi                   | Campana                      |

According to the author, the distribution of water in the 15th and 17th centuries was taken from data found in files at the Municipal Archive of the city (even today, they have not been found). It is observed that there was a great reform change that presumably coincided with the major remodelling at the Carmona Gate between the years 1578-86 when it was transformed from a low Islamic door to a Renaissance door of great height. In essence, the change involved the union of the two great towers forming a building with a rectangular footprint [29]. The distribution of the 17th century is the same as that in the plan of EMASESA; therefore, although the year of the plan is unknown, this table indicates that is occurred in the 17th century. The information about the distribution in the 19th century, according to Gonzalez y Garcia de Meneses, comes from censuses conducted by the architect Manuel Antonio Capo in 1877 and Montanchez in 1888. This report estimate the evolution of the branches and their locations “figure 7”.

Figure 6. Percentage of the distribution of water that went to each branch - customer
Figure 7. Hypothesis of the evolution of the branches of water between the 17th and 19th centuries. The blue branches indicate the 17th century and the orange branches indicate the 19th century.

This report gives another interesting fact: the number of straws owned by each branch. If you compare the number of straws between the different eras, excluding the Real Alcázar, you can see the evolution of water permits and infrastructures in the city in three centuries 'figure 8'.

Figure 8. Evolution of the distribution of water in number of water straws between the 17th and 19th centuries.

It is assumed that the branch of the 17th century, "Medina Sidonia", is the same branch that in the 19th century was named 'Campana' because of its location. The ‘Pilas publicas’ (where San Francisco appears) and ‘San Francisco’ branches of the 19th century are not considered to be the same because of the different pipe size.

5. Conclusions
Determining the flow of water that came to Seville through the aqueduct is not easy because of the different conditioning factors involved in the calculation. For this research, it was necessary to review the existing historical documentation, including several primary sources of information that analysed the flow between the 19th and 20th centuries. In 1877, the engineer Stoffel stated that 4,000 m$^3$/day entered Seville, but this report has been criticized for the low flow given [30]. In 1884, the physician Philippe Hauser testified that the flow that reached the ark was between 4,000 and 6,000 m$^3$/day [31]. In 1889, the engineer González y García de Meneses reported a capacity at the Carmona Gate of 5,870.80 m$^3$/day [32]. At the beginning of the 20th century, Juan Talavera, speaking about the scarcity of water, gave a daily flow of 6,483 m$^3$/day [33]. Therefore, different informants, including others not
mentioned in this article, report that the flow arriving at the ark was approximately 6,000 m$^3$/day. With the data obtained in this study, it is possible to conclude that the aqueduct was capable of transporting more flow than what actually arrived in Seville. Before arriving at the ark, some of the water was diverted to other areas, including the landfills of San Benito and Ranillas, the houses in the Alcalá de Guadaira in Huerta del Rey, the concessions between the Cruz del Campo, the convent of San Agustín, and the spillway of the Madejas [32]. However, considering the flow of water that could originate from the aqueduct in La Florida, much of the water was wasted along the way. According to the data, the percentage of water loss was approximately 36% per day. This loss is partially due to the poor state of the infrastructure resulting from a lack of maintenance and abuses committed by land owners near the aqueduct.

The calculation of the flows of each branch shows that the sum is greater than the amount of water coming from the aqueduct. This information is logical, taking into account the factors involved in the theoretical calculation, because the ark was probably larger than necessary, even if the aqueduct and spring could not meet the demands for which the infrastructure was calculated. Also the ark would contain chops or gates in each branch to cut and control the passage of water to the recipients. If water needed to be removed, the ark had a drain, as shown in the EMASESA plan.

Concerning the distribution of water in the 17th century, according to the percentage of water, if water was available water, the greatest competitors of the Real Alcázar for water in the 17th century were the dukes of Medina Sidonia, whose palace was located in the current Plaza del Duque de la Victoria, 8.

With respect to the change in the distribution between the 17th and 19th centuries, the report of the City Council does not provide the complete number of pipe exits or ‘wounds’ in the censuses conducted in the 19th century, which made it impossible to calculate the theoretical water flow. However, the number of straws and the total flow rate are recorded. Excluding the branch of the Real Alcázar, in the 19th century, there were 375 water straws (coinciding with the EMASESA plan); in the 1887 census, there were 811.25 water straws; and in 1889, there were 817 water straws. Therefore, from the 17th to the 19th century, the flow to other customers increased more than doubled because new branches were opened and greater importance was given to convents and public cells.

With the information obtained in this study, it is possible to get an idea of the distribution of water in the city of Seville through the aqueduct in the 17th and 19th centuries. However, it is be necessary to continue researching the infrastructures and the flow of the water supply. A second phase of research could use the bronze metre at the Municipal Archive to obtain a more accurate hydraulic section, and/or to investigate the water boxes distributed throughout the city to further investigate the water supply of Seville.

Acknowledgements
Thanks to the technicians of the municipal water company (EMASESA), specifically Ignacio L. Rivero Moreno of Graphic Documentation and Ana Patricia García of the Documentary Center, for their collaboration and invaluable help. Additionally, thanks to the surveyor Mimoun Ajmal Aarab for his support and the financial support of the Spanish Commission Interministerial of “Economía y Competitividad” (Plan Estatal 2013-2016 Retos - Proyectos I+D+i) under project BIA2014-55318-R is also acknowledged.

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fountain in the Puerta de Triana (the longest with the ark) and the Plaza de la Magdalena.

[29] M. Valor Piechotta, “The military and palatine architecture in the Muslim Seville.” Diputación Provincial de Sevilla, pp.190, 1991.

[30] L. M. Stoffel, “The waters of Seville: written report on the occasion of the presentation to the City of the studies carried out.” Imprenta y Litografía de José María Ariza, pp. 16, 1877.

[31] P. Hauser, “Medical Studies of Seville.” Tomás Sanz, pp. 25, 1884.

[32] A. González y Garcia de Meneses, “Determination of equivalence between water straw and cubic meter.” Imprenta y Litografía de José María Ariza, pp. 26-28, 1889.

[33] P. Hauser, “Medical Studies of Seville.” Tomás Sanz, pp. 25, 1884.