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Modelling the Water Supply System of the National Palace of Queluz Gardens
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ABSTRACT

The gardens of the National Palace of Queluz, built in the eighteenth century, are supplied by a complex branched water supply system. The aim of the current research is to analyse the hydraulic behaviour of the pressurised supply systems, namely the water pathways, the available pressure-head at the fountains and the water consumption at the gardens, by means of computational simulation for different operating scenarios. Results show that the difference of elevation was sufficient to assure the water transport by gravity from the surrounding water sources to the ornamental fountains, cascades and lakes and to provide 8-12 m water jets. Several scenarios are analysed showing that the fountains and cascades water consumption are in the range of 12.4 to 42.2 L/s, available water sources are enough to satisfy these demands for several hours per day and the two existing tanks, Curro and Miradouro, have sufficient capacity to store water to be used in the ornamental fountains and cascades and in the irrigation of the botanical garden and the horticultural area.

Keywords: Historical hydraulic systems; smart systems; choice of plants; contemporary gardens; sustainability.

INTRODUCTION

The National Palace of Queluz is one of the most emblematic monuments of Portugal, an example of harmonious connection between landscape and architecture. Its construction was divided in three phases: the first one from 1747 to 1758, the second one from 1760 to 1786, during which the construction of the gardens took place, and a third phase from 1786 to 1792 (AIRES-BARROS *et al.*, 2012). The French Jean-Baptiste Robillion, an architect, sculptor and a goldsmith, was responsible for the layout and aesthetics of the various gardens in the palace, framed in the principles established by the gardening treaties of the time, with a very strong and clear French influence on the gardens constructed by Le Nôtre (AIRES BARROS *et al.*, 2015). The complex hydraulic systems to allow water to flow into the palace gardens were directed by the court engineer Manuel da Maia, one of the great collaborators of Lisbon's reconstruction. These hydraulic constructions were of extreme importance both for the gardens and fountains aesthetics but also for the functionality within the palace (MATOS, 2017). It was Manuel da Maia's work, as an engineer and Robillion architecture skills, that made possible the link between beauty and functionality in the gardens.

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In this paper, the hydraulics of the water supply system to the gardens of the National Palace of Queluz are studied based on computational simulation using the software tool EPANET (ROSSMAN, 2000). The aim is to identify the available pressure head at the fountains and the main water pathways within the system. In addition, the amount of water consumed in the gardens for aesthetic purposes is estimated.

The gardens built in the surroundings of royal sites in the Iberian Peninsula during the renaissance period shared many common features. The existence of upper reservoirs or dams, located at a higher elevation, is a typical characteristic of the hydraulic systems of such gardens and it denotes the influence of the Roman hydraulic tradition in the Iberian Peninsula (TORIBIO MARÍN, 2020). The dams and tanks allowed to store water and, most importantly, allowed the water to flow by gravity in the downstream supply systems. In addition, in many gardens, water tanks also served as water mirrors, providing great aesthetic value (RODRIGUES *et al.*, 2011; RODRIGUES & TORIBIO Marín, 2020). This feature is found in many hydraulic systems of gardens, similar to the one of the National Palace of Queluz, in which water plays a major role for the gardens aesthetics and irrigation, like Aranjuez, Casa de Campo, Valsaín, El Escorial, La fresneda and El Bosque de Béjar (TORIBIO MARÍN, 2020). These water supply systems shaped the way gardens and palaces were spatially organized, depending on the water transportation infrastructures that best fitted the topography of the sites. Available water was (and still is) scarce in arid areas like the Iberian Peninsula in comparison to the high water demand of the gardens and so all of the water sources located nearby every location (rivers, streams and underground sources) had to be explored. In Valsaín, several infrastructures were built, among them six dams that received water trough channels further connected to the Queen's Garden fountain. Like in Valsaín, the gardens spatial distribution in El Bosque de Béjar were influenced by the reservoirs construction. In Casa de Campo, five dams were built at higher elevations than the gardens (located in a valley), allowing enough water pressure head to form high water spurts at the famous Neptune Fountain. his solution was repeated for La Fresneda due to the site's topography similarities. Water was collected from the several streams located nearby and transported by gravity to lower elevation points (i.e. gardens, palace).

The dams' construction differed in terms of spatial allocation and, in the case of Valsaín and El Bosque de Béjar, they were incorporated in the gardens aesthetics. For the case of Aranjuez, Casa de Campo and La Fresneda royal constructions it is the opposite, the dams were located further away from the royal places, being an external functional accessory to allow water supply (TORIBIO MARÍN, 2020).

This typical hydraulic system layout guaranteed enough pressure to make possible the water “shows” at the several fountains and irrigation systems to work. In this sense, it was not the royal properties and their gardens that influenced the hydraulic constructions, but the other way around. Gravity was the main force and gravity based systems were unavoidable to make the water supply possible. For this reason, each site was carefully chosen in terms of water availability (whether rivers, streams or other underground sources) and terrain topography (sloppy terrains were preferred to allow gravity fed water systems).

METHODOLOGY

Water supply system description

The National Palace of Queluz and its gardens are located in Queluz, a city in Sintra Municipality, in the Lisbon District, Portugal. The location is surrounded by several natural water sources (e.g., springs, streams) which must have been one of the main reasons why this location was chosen for accommodating the palace (Fig. 1). Besides the need to supply water to the palace, it was also needed to provide water to the gardens and its numerous cascades and decorative fountains, as well as to irrigate the adjacent botanical and horticultural areas. The topography

Fig. 1. Satellite view of the Palace and main water streams: Jamor River (purple), Forcadas stream (green) and Carenque stream (yellow) (source: Google Earth 2020).

Fig. 2. Scheme of the water supply system of the National Palace of Queluz and its gardens (adapted from Correia 2015).

Fig. 3 a,b, c, d, e, f. Selected fountains and cascades from the gardens of the National Palace of Queluz. (a) Neptune fountain (Bernini), (b) Medallions fountain, (c) Great cascade, (d) Shell cascade, (e) Monkey fountain, (f) Shell fountain.

is another characteristic of the site that enables the water transport by gravity from the natural sources (water mines) to the fountains and cascades.

A complex hydraulic system was built at the National Palace of Queluz (Fig. 2) to transport water from the palace surroundings and to distribute the water to the numerous fountains and cascades of the gardens. This system included aqueducts and buried pipes that transported water from springs and streams nearby the palace area. The water was conveyed by gravity due to the difference in elevation between the water sources and the palace.

In the current work, the water supply infrastructure of the gardens was drawn using AutoCAD 2020 (Autodesk), based on existing nineteenth century maps (Fig. 2) and other information found in literature (*Planta das minas e encaamentos d'água do Almojarifado de Queluz*, 1901), regarding the description of water flow path and the pipes materials (iron, lead). In the absence of information regarding the source of the water supplying the Dragon fountain (see item 35, in Fig. 2), it was assumed that an additional pipe would connect it to the Shell cascade (see item 20, in Fig. 2), located nearby and at a higher elevation.

The water supply system scheme was composed of four main subsystems as presented in Fig. 4, namely, Terra Grande, Curro, Miradouro e Quatro Bicas subsystems.

Terra Grande subsystem, represented with the purple lines in Fig. 4, conveyed water from the Terra Grande spring and from Forçadas stream through an open canal to the palace gardens for irrigation of the botanical garden and of the horticultural area. Since the flow in this system is a free surface flow, it does not have any fountains, not being analysed in the scope of this study.

Curro subsystem, represented with the red lines in Fig. 4, connected Tascoa spring and Tijolo and Olheiro spring to the Curro tank (see 10, Fig. 4) by means of a lead pipe. Curro tank distributes water to the Neptune (Bernini) (see 14, Fig. 4) and the Medallions fountains (see 15, Fig. 4).

Miradouro subsystem, represented with the green lines in Fig. 4, transported water from several springs located in Monte Abraão and Pendão through Ponte da Pedrinha aqueduct to Miradouro tank (see 12, Fig. 4). From this tank forward, water is transported through pressurized iron pipes to the fountains of the Hanging and Malta gardens (see 22, 23, 24, 25, 29 and 30, Fig. 4), ending its path in the Great Cascade (see 16, Fig. 4).

Quatro Bicas subsystem, represented with the blue lines in Fig. 4, conveyed from Carenque stream flows with free surface through Principe da Beira aqueduct to Quatro Bicas fountain (see 17, Fig. 4). From there, a pressurized pipe system transported water to the palace, to the kitchen, the Embrechados garden, the Lontra terrace fountain, the church and the clock tower (see 19, 31 and 36, Fig. 4). Later on, in 1896, a pipe was built connecting Quatro Bicas fountain and Carranca fountain (see 18, Fig. 4). From there, water would flow to the reservoir underneath the Hanging garden and then to the botanical garden (see 33, Fig. 4).

Fig.4. Schematic representation of the water supply and irrigation system of the National Palace of Queluz.

Hydraulic modelling of the gardens' water supply network

The three pressurized subsystems (Curro, Miradouro and Quatro Bicas) were drawn in AutoCAD 2020 and converted into an EPANET model (ROSSMAN, 2000). Terra Grande subsystem was not analysed, since water flows in an open canal and was used for irrigation purposes only, not having any fountains or cascades.

Elevation data were obtained from Google Earth platform. In the lack of more reliable information and based on photographs of the iron water pipes during a rehabilitation intervention that was carried out recently (Ana Duarte Rodrigues' personal archive), 150 mm diameter was considered for all pipes of the water supply system of the palace gardens. These pipes were assumed to be made of cast iron with a Hazen-Williams roughness coefficient equal $130 \text{ m}^{0.37 \text{ s}^{-1}}$ (this coefficient is relevant to calculate friction losses in pipes).

Each of the subsystem is composed of one source tank with constant head, a set of pipes with constant diameter and junction/extreme-end nodes with an assigned consumption. This consumption was specified according to the fountain/cascade type (I or II) and to the demand scenario analysed (1, 2 or 3), since no values of flow rate were found reported in literature.

The decorative fountains and cascades were divided into two main types, according to the area of the lake and to the number of water spurts (Table 1). Type I is associated with smaller lake surface area (between 3 and 55 m²) and few water spurts (less or equal than four), with the exception of Gate of fame which was considered to be Type I because it does not have any water spurts. Type II is associated with a larger area (higher than 55 m²) and/or higher number of water spurts (more than four), with the exception of Nereide fountain and shell fountain, due to the high number of water spurts. Cascades were also considered Type II due to their large size. Table 1 shows the fountains and cascades associated with each type as well as their estimated water surface area and number of spurts.

Table 1 Categorization of each fountain and cascade of the National Palace of Queluz.

Type I			Type II		
Fountain name	Area (m²)	Water spurts (no.)	Fountain name	Area (m²)	Water spurts (no.)
Lontra terrace fountain	14	≤ 4	Neptune fountain (Bernini)	92	> 4
Carranca fountain	11		Medallions fountain	94	
Monkey fountain	11		Great Cascade	-	
Fountain	5		Shell cascade	-	
Gate of fame	88		Neptune Fountain	62	
Dolphin fountain	55		Nereide fountain	35	
Dragon fountain	12		Shell fountain	11	
Embrechados garden fountain	34				
Botanical garden fountain	35				
Palace fountain	3				

Assessment of the water consumption at the gardens

In the pressurized water supply system, once the water would go out of the pipes in the numerous spurts of the fountains, it was stored in the lakes and could only be used for irrigation or simply discharged to the streamline. Consequently, the water that was used for decorative purposes at the fountains and cascades was consumed for irrigation of the gardens.

Since no quantitative information was found in literature, three demand scenarios were established and analysed (Table 2) to quantify the water consumed in the gardens for ornamental purposes only, based on known water flowrates at the domestic level. A domestic tap has a flow rate between 0.08-0.15 L/s; assuming an average value of 0.1 L/s and considering that type I fountain has 5 spurts (each with a similar consumption as a water tap) and type II has 8 spurts, this would result in a total demand of 0.5 and 0.8 L/s, respectively. These consumptions correspond to scenario 1. The other two scenarios 2 and 3 consider to an increase of 0.5 and 1 L/s on the previous values. In these scenarios, all fountains and cascades were simultaneously consuming water, which corresponds to the most critical situation in terms of water consumption. The water consumed at the fountains was compared with the available water in the surrounding water sources. In addition, the time that the water spurts could work without depleting the upstream tanks was estimated.

Table 2 Water demand at the fountains in each of the three scenarios

Scenario	Water demand at the fountains (L/s)	
	Type I	Type II
S1	0.5	0.8
S2	1.0	1.3
S3	2.0	2.3

RESULTS ANALYSIS

The hydraulic model allows the identification of water flow pathways in the three subsystems, the assessment of the available pressure head at the fountains for different operating scenarios and the quantification of total water consumption in at the ornamental fountains and cascades. These issues are addressed in the following sections.

Nodes elevations and water flow pathways

The elevations of the nodes and the water flow pathways in the three subsystem are depicted in Fig. 5. Elevations in Curro subsystem vary between 106.00 and 94.00 m, in Miradouro subsystem between 114.00 and 90.00 m and in Quatro Bicas subsystem between 100.00 and 86.00 m. The maximum elevation difference between the supply tanks and the consumption nodes (fountains and cascades) is 12, 24 and 14 m, respectively, in the previous three subsystems. These differences, higher than 10 m, indicate that, if head losses in pipes are small, there is sufficient pressure-head at the fountains to generate high water spurts. This will be quantified in the next section.

Fig. 5. Elevation of the nodes in the three pressurized subsystems: (a) Curro tank subsystem (b) Miradouro tank subsystem (c) Quatro bicas subsystem.

Pressure-head and hydraulic performance of the systems

The three scenarios were simulated using EPANET for the three pressurised pipe systems, namely, Curro subsystem, Miradouro subsystem and Quatro Bicas subsystems. Results are presented in the following paragraphs.

Curro subsystem

Figure 6 presents the numerical results obtained for Curro subsystem in terms of pressure-head at the nodes of the two extreme operating scenarios 1 and 3. Results show that the available pressure-head at the two fountains – Neptune (Bernini) and Medallions fountains – are of 7.00 and 12.00 m, respectively (Fig. 6). These values correspond to the maximum height reached by the water jets at the fountains, since the nodal pressure-head, $h = p / \gamma$, is converted into water velocity in the spurts according to Torricelli velocity law, $u = \sqrt{2gh}$, in which u is fluid velocity (m/s), g is gravity acceleration (m/s²), h is pressure-head (m), p is pressure (Pa) and γ is water specific weigh.

Additionally, the small water demands at the fountains and cascades in both scenarios, though operating simultaneously, transported in the 150 mm pipe diameters result in low flow velocities in the pipes and very low head losses between the tank and the fountain.

Differences in the pressure-head and in the flow velocity in scenarios 1 and 3 are minimal. For instances, pressure head at node15 is 11.99 m in scenario 1 and 11.91 in scenario 2.

Fig. 6. Pressure-head at the fountains and cascades and flow velocity in the pipes in Curro Subsystem for (a) scenario 1 and (b) scenario 3.

Miradouro subsystem

Fig. 7 presents the numerical results obtained for Miradouro subsystem in terms of pressure-head at the nodes for the two extreme operating scenarios 1 and 3. These results show that the pressure-head at the main fountains Neptune, Nereide and Dolphin and at the top of the Great Cascade are in the range of 8.00 to 13.00 m, depending on water demand scenario considered (Fig. 7). This subsystem includes one of the principal groups of fountains (fountains located in Pensil and Malta garden) and the Great cascade. The results of the modelling demonstrate that the water can flow by gravity in the pressurized piped system, as the pressure head is enough for the water to reach all fountains, including the tank on top of the Great Cascade (see node 16, Fig. 7), since the available pressure head is 12.24 and 8.24 m in scenarios 1 and 3, respectively.

These results also show that the Great Cascade can be supplied by the Miradouro tank (see node 12 in Fig. 7) but could not be supplied by the Curro Tank (see node 10, Fig. 6) as the elevation difference between the two locations is small (close to 6 m) and would barely be enough for the water to reach the top of the Great Cascade.

Fig. 7. Pressure-head at the fountains and flow velocity in the pipes of the Miradouro subsystem for (a) scenario 1 and (b) scenario 3

Fig. 8 shows a photograph of the dolphin fountain (see 30 in Fig. 7) indicating the potential height of the water jet (available pressure head is 9.49 m for scenario 3), which illustrates that the water jets could go almost as high as the palace height (estimated to be around 10 m). This fact was described by Pires (1925-1926): “it threw water over the roof of the palace”¹.

Fig. 8. Dolphin fountain (30), located in Malta garden. Represented in a blue arrow is the height of the water jet in comparison to the height of the palace.

1 Original text in portuguese: “vomitava água por cima do telhado do palácio” (PIRES, 1925-1926)

There are other descriptions in Pires (1925-1926) of the water show created by the several ornamental fountains and the Great cascade that corroborate the height of water jets, as the following: “The gardens offered a show and a magnificence never seen. From all the fountains, water was drawn in many ways, at the bottom of the park the cascade showed all its wonderful effect”² and “With the prince they went for a walk in the gardens, where the water spurts from the fountains were on, which caused them a big admiration for its magnificence and greatness”³. These descriptions are in agreement with the hydraulic calculations carried out herein, demonstrating that the water jets in the fountains and cascades were indeed very high and created a wonderful water show.

Quatro Bicas subsystem

Fig. 9 presents the numerical results obtained Quatro Bicas subsystem in terms of pressure-head at the nodes of for the two extreme operating, scenarios 1 and 3. In most of the Quatro Bicas subsystem, the available pressure head at the consumption nodes is low (lower than 3 m) for both scenarios, except in the fountain at the botanical garden (see 33 in Fig. 9). This is due to the small elevation difference between the water source (the Quatro Bicas fountain) and the water consumption locations. However, the available head in Quatro Bicas subsystem is enough for the water uses in this system, as it does not include the main fountains and lakes of the gardens.

Fig. 9. Pressure-head at the fountains and flow velocity in the pipes of the Quatro Bicas subsystem for (a) scenario 1 and (b) scenario 3.

The water demand increase from scenario 1 to 3 result in an increase of the water velocity in the pipes and to a decrease in available pressure head at the fountains. However, the simulations carried out in EPANET show that the system can cope with such increase in water demand and still be able to supply the fountains and the cascades. Overall, the results show that the design of the complex water supply system of the gardens allows it to cope with great variations in water demand, such as the increase in demand from scenario 1 to 3.

2 Original text in Portuguese: “os jardins ofereciam um espetáculo e uma magnificência nunca vistos pelos arrais. De todos os lagos a água repuxava de variadas maneiras, ao fundo do parque a cascata mostrava todo o seu maravilhoso efeito(...)” (PIRES, 1925-1926)

3 Original text in Portuguese: “Com o Príncipe foram dar um passeio pela quinta, tendo mandado abrir os repuxos dos lagos, que lhes causaram grande admiração, pela sua magnificência e grandeza” (PIRES, 1026)

Water consumption at the ornamental fountains and cascades

The total water flow rate consumed at the gardens for aesthetic purposes for each of the three analysed scenarios calculated by EPANET is presented in Table 3. These values are compared with the available water flow rate in the natural sources surrounding the National Palace of Queluz, which is, on average, 32 L/s, including the summer period (Henriques *et al.*, 2006).

Table 3. Total flow rate consumed in the subsystems for each scenario.

Subsystem	Water consumption (L/s)		
	Scenario 1	Scenario 2	Scenario 3
Curro	1.6	2.6	4.6
Miradouro	8.3	14.8	27.8
Quatro Bicas	2.5	5.0	10.0
Total	12.4	22.4	42.4

The most water demanding conditions correspond to scenario 3 (42.4 L/s) which exceed the local average available flow-rate (32 L/s). This suggests that water was continuously stored in the upstream tanks to cope with consumption needs of the ornamental fountains, which were operated during a limited number of hours per day, and those of the irrigation. This results show that the water consumption at the gardens for decorative purposes would be in the range of 12.4 to 42.4 L/s, or 45 to 152 m³ per hour.

Assuming that stored water in Curro and Miradouro tanks was only used for supplying the decorative fountains and that no water was entering in the tanks, the maximum time that the water spurts could simultaneously operate is presented in Table 4 for the three scenarios. The results suggest that each subsystem was not designed to operate continuously, but to work only a limited number of hours during the day; otherwise, the available water would not be sufficient for irrigation of the botanical garden and of the horticultural area. The Quatro Bicas subsystem is not considered in this analysis, since it does not have any storage capacity nor does it include the main fountains and cascades of the gardens.

Table 4. Estimated maximum working time for the main fountains and cascades (subsystems Curro and Miradouro) for the three scenarios

Subsystem	Tank volume	Maximum time (hours)		
	(m ³)	Scenario 1	Scenario 2	Scenario 3
Curro	250*	43	27	15
Miradouro	1130**	38	21	11

Note: *Value estimated based on surface area measured in Google Earth and assuming 1 m of water height;

CONCLUSIONS

The National Palace of Queluz and its gardens are located in a perfect area regarding water availability and topography, which enabled water to flow by gravity to the many ornamental fountains and cascades of the gardens with enough pressure for the fountains to function and for the water to reach the top of the Great Cascade. The gardens water supply system is composed of a free surface canal flow, the Terra Grande subsystem, and three pressurised pipe systems: Curro, Miradouro and Quatro Bicas subsystems.

A complete analysis has been carried out of the three pressurised pipe systems. Three demand scenarios at the fountains have been considered. Results have shown that two subsystems, Curro and Miradouro subsystems, have enough pressure head to assure high water jets in the fountains up to 8-10 m and that the Quatro Bicas subsystem has a very low pressure head at all nodes (lower than 3 m), reason why it does not supply any relevant fountain or cascade.

The overall water consumption at the gardens for decorative purposes are in the range of 12.4 to 44.2 L/s. Available water in mines and wells was stored in two main tanks, Curro and Miradouro tanks, to cope with water resources variability during the year. Given available water sources, which are on average 32 L/s, Curro and Miradouro fountains and cascades were designed to operate simultaneously only a limited number of hours during the day, otherwise, the available water would not be sufficient for the irrigation of the botanical garden and of the horticultural area.

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