Engineering, Geology and the Water Supply to Lisbon in the Second Half of the Nineteenth Century. Expertise and Innovation

José Manuel Brandão and Pedro Miguel Callapez

Abstract

Highlighting the city of Lisbon as a case study, this chapter focuses on the pioneering role of the earliest geologists who introduced Geology, its concepts and its methods as a key tool in the search for drinkable water. This paradigmatic change occurred in the 1850s, due to the work of Carlos Ribeiro, Chief Engineer of the Department of Mines in the Ministry of Public Works, and the first director of the Kingdom's Geological Commission, founded in 1857. Invited to submit his advice about the plans for the Lisbon water supply, Ribeiro was convinced that only detailed geological fieldwork could provide the knowledge for accurately predicting the occurrence of groundwater. For this purpose, he carried out detailed lithological and structural studies on the northern and eastern ranges of the city, subsequently becoming able both to redefine and map the main stratigraphic units and to characterize those with better quality aquifer properties. The knowledge and experience generated by this pioneering work was followed by several contributions by Nery Delgado, his right-hand man, and by their colleague, renowned geologist Paul Choffat. Taken together, these works may be considered as the true precursors of modern hydrogeological studies in Portugal.

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1 Introduction

Considering the Portuguese context of the nineteenth and twentieth centuries, the water supply to Lisbon stands out as a paradigm, due both to its history and to the construction of technical monuments that brought together remarkable personalities who actively collaborated in a network of scientific and technological exchange. From an administrative point of view, the example of the Portuguese capital illustrates the coeval and international transition settings of financial liabilities for the management of water facilities, ranging from the traditional municipal sphere to the private sector, an example that also inspired other municipalities to adopt the same basis. This sort of water revolution happened broadly and simultaneously throughout Europe, with most countries advancing the construction of their water distribution and sewerage systems against the controversial debate backdrop of the municipalisation versus privatisation of these public services. This process was led by Great Britain, especially after Chadwick's important Report on Sanitary Conditions (1842) was published, and by France, with the "haussmannisation" of Paris.

While the functionalities of hydraulic engineering and industrial architecture were instrumental to the construction of the several structures that typify the city's supply system in the period under review, a new disciplinary field also began to impose itself as a strategic tool for deployment in the upstream phases of engineering works. The profile of Geology was raised by one of the most notable Portuguese pioneers in this field, the engineer Carlos Ribeiro (1813–1882),[1] head of the Department of Mines of the Ministry of Public Works, Commerce and Industry and, after August 1857, the director of the then-founded Geological Commission of the Kingdom. In historical praise, his right-hand man, Joaquim Filipe Nery Delgado (1835–1908),[2] also a military engineer, stated, "[I]t was this Man who had the glory

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[1] Carlos Ribeiro studied artillery and military engineering at the Royal Navy Academy, the Army School, and, later on, at the Polytechnic Academy of Oporto. After 1845, he started working as a civil and mining engineer in the Public Works Company of Portugal and in the Farrobo and Damásio Company, concessionaire of the coal mines of Cape of Mondego and Buçaco. Between 1852 and 1857, Ribeiro was head of the Bureau of Mines, of the new Ministry of Public Works, Commerce and Industry. After this period, and until his death in 1882, he directed the Geological Commission of the Kingdom. His prior geological sketches formed the groundworks for the first complete geological map of Portugal (1:500,000), which was the primary goal of the Commission, published in 1876. As a researcher with multiple talents, Ribeiro left a huge amount of work in the applied areas of engineering, geology, hydrology and mining. His interest in prehistoric archaeology was also the focus of a famous controversy about the existence of humankind in Tertiary times. While on a mission to several European countries (1858), he became acquainted with the most prominent Earth Sciences experts of the time, starting regular scientific correspondence with many of them. Ribeiro was also a member of many Portuguese and foreign scientific societies and was distinguished with several national and international awards (Delgado 1905).

[2] A military engineer from the Polytechnic School of Lisbon and the Army School (1856), Nery Delgado joined the Geological Commission of the Kingdom in 1857, becoming its Director after the death of Carlos Ribeiro. His huge body of scientific work in the fields of Palaeozoic stratigraphy and palaeontology, applied geology and prehistoric archaeology was internationally recognized and recorded in many publications. Together with Ribeiro, he signed the first full

of being the first to recognize the stratigraphy of the country, and to determine the relative ages of the geological units before the organization of the Commission" (Delgado 1905: 21).

Thanks to his prestige and influence in this scientific field, Ribeiro was invited, on three separate occasions, to express his opinion on the projects that the Municipality of Lisbon and the Water Company had proposed to the Portuguese government. His suggestions and criticisms were based not only on his in-depth knowledge of the geological units and structures recognized in the Lisbon peninsula, but also on the expertise and work of several renowned European hydrologists. His opinions were not always taken in good faith; however, time proved their worth, clearly demonstrating the value of geological knowledge as a basis for the study of water for public consumption, and thereby ending the previously prevailing empiricism, hitherto in use for centuries.

Many authors have delved into the historiography of the Lisbon water supply from the eighteenth century to the twentieth century. These studies have focused on its primary hydraulic and mechanical infrastructures, such as the Águas Livres (Free Waters) Aqueduct (eighteenth century) and the Barbadinhos steam pumping station (1880), and on the economic aspects of the two Lisbon water concessionaires. In addition, there has also been some research into their management, their framework within national policies for the sector and the permanent tensions between the government and the stakeholders (e.g., Silva and Matos 2004; Costa and Vital 2005; Schmidt et al. 2005; Bruno and Inácio 2014; Saraiva et al. 2014; Pato 2016). Far from these domains, the present text instead intends to approach the historical application of geological knowledge as a means of revealing potential aquifers.

As it is unfeasible to cover all of the late nineteenth century projects in which Geology emerged as the guiding discipline in the search for and collection of water for public consumption, mostly undertaken by the tutelary members of the Geological Survey, Carlos Ribeiro, Nery Delgado and Paul Choffat (1849–1919),[3] the present contribution highlights the pioneering actions of the leading figure in achieving the huge desideratum that was the supply of drinkable water, in quality and quantity, to Lisbon, as had already been achieved in Europe's other main cities.

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geological maps of the country (1:500,000), presented at international congresses, where he represented Portugal. Delgado was a member of several national and international scientific institutions and maintained a close correspondence with many well-known names from foreign institutes and universities (Choffat 1909).

[3] Born in Switzerland, Paul Choffat graduated in Chemistry and Natural Sciences from the University of Zurich. Following an invitation from Carlos Ribeiro, who met him in Paris during the International Geological Congress of 1878, he travelled to Portugal with the purpose of studying the local Mesozoic stratigraphy and palaeontology. Due to work and personal health issues, he remained in Portugal for nearly 40 years. During this period of intensive scientific research at the Geological Commission, he authored a vast bibliography, with extensive monographs on the Jurassic and Cretaceous formations. Besides stratigraphy and geological cartography, his work also included updated and rigorous studies in the fields of tectonics, hydrology, applied geology and mineral resources (Rocha et al. 2008). Choffat was an internationally reputed geologist, a member of several scientific societies and an authority on Mesozoic stratigraphy.

2 Historic Waterworks Predating the Concessions

One of the first major hydraulic works for supplying water to Lisbon was the *Olissipo* Roman dam, located about 10 km NW of the primeval city and built around the second century to exploit the Carenque stream springs (Almeida 1969; Quintela and Mascarenhas 2006). The dammed waters represented a volume of about 125,000 m^3, transported via an aqueduct that remained operational until around the mid-sixteenth century, with its reconstruction even being recommended by the painter and humanist Francisco de Holanda (1517–1585) as a means of dealing with the extreme water shortage that was then being experienced in the capital.

The outline of this precursory structure also served as the basis for the suggestions made by Leonardo Torriani (*c*. 1560-–1628), an Italian architect in the service of King Philip II of Portugal (Philip III of Spain), for the construction of a new aqueduct to transport spring water, known as the "Águas Livres" aqueduct, from the Carenque valley, northwest of Lisbon, to the city (Ribeiro 1867). However, given the substantial investment required, constructing the Águas Livres Aqueduct only began in 1731, during the reign of King João V, when the national financial distress that had previously prevailed found relief through the annual shipments of gold and diamonds from Brazil.

Built with the contributions of some of the most relevant names in Portuguese military engineering and architecture of the time, including Manuel da Maia (1677–1768) and Carlos Mardel (c. 1696–1763), this massive and majestic aqueduct (Fig. 1) underwent expansion during the second half of the nineteenth century in order to allow for capture and transport from more natural springs. The aqueduct was based on a complex water collection, adduction and distribution system, which covered a *continuum* of 58 km of underground and aerial galleries, built into the local limestone stonework and concluded in 1799.

With the help of gravity, the Carenque waters began flowing through the aqueduct in 1748, long before the conclusion of the Mãe d'Água das Amoreiras Reservoir, built in a topographic relief located near the city, where the water system ended. This was an enormous covered tank with a 5500 m^3 capacity, built to serve as a reservoir and act as a control site for distribution to a small network of magnificently decorated fountains within the city. It was finished in 1834 (Andrade 1851) and drew substantial criticism from the population of Lisbon, not only because of its delay, but also due to the poor quality of its waters. From then onwards, the city received about 1900 m^3 of water per day during the dry season. This caudal corresponded to a daily average of 15 L per habitant, a level of consumption that, although considered "good for the epoch" by some authors (Branco 1957: 6), was actually insufficient for the needs of a growing city.[4]

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[4] According to Bruno and Inácio, this great hydraulic work "was not, in terms of a solution to the lack of water problem of Lisbon, an investment with any medium or long-term planning perspective" (2014: 10). This was subsequently reflected in the need to reinforce the capacity in the late nineteenth century.

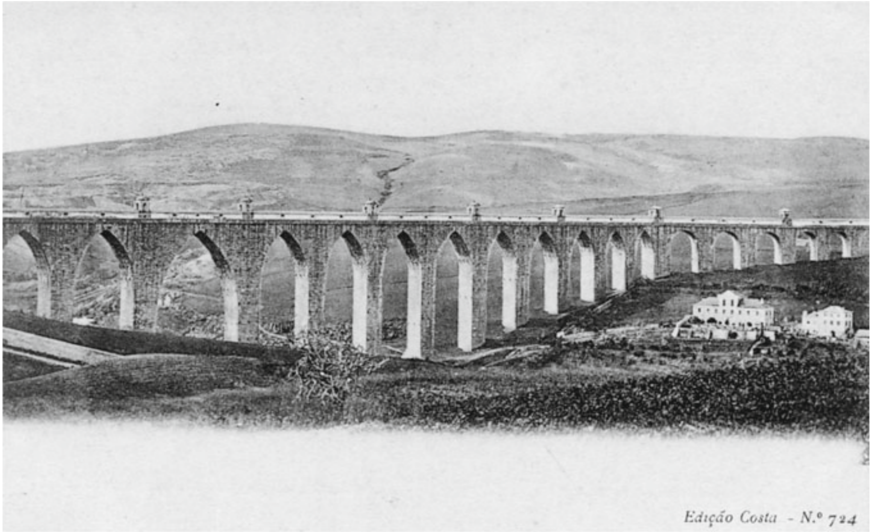

Fig. 1 Arches of the Águas Livres Aqueduct. Classified as a National Monument since 1910, this eighteenth century structure has long been considered an *ex-libris* of Lisbon. Postcard, *c.* 1900

Fig. 2 Water supply at a public fountain in Lisbon. *Photo* Joshua Benoliel, 1907. Municipal Photo Archive, Lisbon, JBN-1228

Only some public services, individuals holding contracts with the Municipality, or anyone who owned properties with springs adjoining the aqueduct received water directly from this structure (Andrade 1851). The rest of the urban population drew their supply freely from the fountains or bought water distributed by water carriers in 25 L barrels, an activity subject to City Council regulation (Ferreira 1981) (Fig. 2).

3 Pezerat's Proposals and Ribeiro's Opinion

In pursuit of the innovations brought about by the Industrial Revolution and their benefits, the Lisbon of the 1850s was struggling with various structural and planning problems stemming from a population growth of over 150,000 inhabitants. Furthermore, the absence of hygiene and sanitation along the public roads of this expanding urban area caused recurrent epidemiological outbreaks, specifically of typhus, cholera and yellow fever (Gomes 1866).

In response to this calamitous situation, the government was authorized to contract, through a public tender, a company able to guarantee an acceptable water supply to Lisbon (Decree from December 22, 1852). In the meantime, entrusted with the administration of Águas Livres, the Municipality appointed the engineer Pedro José Pezerat (1801–1872)[5] to carry out studies on how to solve the problem, correspondingly already foreseeing the possibility of a future commercialization of the service. Water was turning into a commodity everywhere.

Pezerat presented several solutions to the City Council, based on the studies that he had been conducting since 1846 (Pinto 1989). Part of his scrutiny focused on the "Bairro Oriental" (Eastern Quarter), one of the oldest urban nuclei of Lisbon, which was supplied by several natural springs, some of them collected by large fountains, such as Dentro and Lavadeiras in the inner city, or El Rei and Praia, located in the medieval quarter of Alfama, close to the Tagus River. He proposed to assemble all of these primary water sources through the construction of a large mine with a course running parallel to the river and the lower zones of the city. This would cut off all of the local aquifers, which might then provide 4000 m^3 per day, and, once combined and raised to a height of 60 or 70 m, through recourse to a steam engine (30 hp), they would then be able to distribute water to the highest areas of the city (Pezerat, *in* Câmara … 1853).[6]

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[5] Born in France, Pezerat studied civil engineering and architecture in Paris (1821). After spending some years working in Brazil and Algeria, he came to Portugal, in the late 1840s, where he initiated a collaboration with the Municipality of Lisbon. In 1852, the Municipality hired him as an engineer, entrusting him with the water supply works for the city. His activity quickly extended to urban planning and municipal works. For about 20 years, he proficiently ensured the leadership of the Technical Department of the Municipality, where he was responsible for numerous studies, projects and opinions (Paixão 2007).

[6] For reasons of coal economy, Pezerat recommended the acquisition of an engine from Alexander Hermanos from Barcelona, instead of a Cornish type (Pezerat 1855: 18).

Since this project was based on the existence of an artesian water table supplied by infiltrations in the terrigenous and carbonated beds of the local Cenozoic units, the City Council requested a judgment from experts at the Polytechnic School of Lisbon, namely, the Professor of Mineralogy, Francisco Pereira da Costa (1809–1889), and the chemist Júlio Simões Pimentel (1809–1884), who came out in favour of the utilisation of those waters (Câmara … 1853).

However, Pezerat's most important proposal was to dam the rainwaters and springs in Quintã, Carenque Valley, and to close the site where the Roman dam had once existed, allowing for the creation of a large "*conserva*." This shallow reservoir would provide water of better quality to Lisbon, through the Águas Livres Aqueduct, with a volume six times greater than that then available.

> (…) the waters from surface springs, like those that cater to the aqueducts of Lisbon, are charged with vegetable principles (*sic*.) in dissolution, together with organic elements, salts and sediments in which they saturate themselves. They cannot be free of these unless they are filtered in sandy substrates below the surface. On the contrary, the flowing waters gathered in vast and deep deposits in which they begin to accumulate their sediments, and to evaporate the lethal gases that they may have absorbed, purifying themselves, are naturally and generally more appropriate to everyday life uses (Pezerat *apud* Andrade 1851: 352).

Aware that underground waters were naturally filtered when flowing over great distances, Pezerat also considered the possibility of drawing on the spring water available in downtown Lisbon. As a whole, the works proposed were to provide approximately 16,400 m^3 of water per day to the city (Ribeiro 1867), which reflected a considerable quantitative leap in the city's supply.

The dam, which was never built, was contested by the Public Works engineer Augusto de Carvalho (1838–?), who believed that it could become a site for the disposing of filth, a place for washerwomen or even an animal cemetery. As an alternative, he defended the development of the Francesas aqueduct, a subsidiary element of the main structure, whose waters sprang from basaltic rocks, and were therefore "lighter, clearer, pleasant to the taste and less saturated with strange matter" than those from the main aqueduct, which he classified as "heavy, thick, unpalatable and saturated with salts and calcareous substances" (Carvalho 1853: 41).

The Municipality then asked Carlos Ribeiro to provide his opinion on this project. The goals involved evaluating the local conditions of soil permeability for water retention and verifying whether the extent of the hydrographic basin was sufficient to provide the amount of water promised for summertime without the risk of the reservoir becoming a source of infection due to its scarce water column.

According to the observations made in the field work carried out in 1853, the Carenque stream flowed in a thick succession of limestone beds dipping to the south, cut by the diaclases normal to such stratification planes. These levels overlaid a calcareous conglomerate and, below, there was a large set of mainly coarse sandstones outcropping northwards, which reached far beyond the boundaries of the drainage basin studied. Ribeiro had no doubts about attributing the Lower Cretaceous age to this fossil-rich sedimentary succession. He also concluded that the coarser beds were being soaked in water until they were saturated and that the water moving through the sediments was being retained by clayish beds, which behaved as impermeable layers, able to store the waters due to be dammed.

Ribeiro also focused on the local and regional tectonics, as he believed that their remote activity might have been decisive in the structural setting of the Cretaceous units. He was mostly concerned with the detached fault planes and diaclases, as they constituted zones of weakness within the rocky massif, enabling the infiltration and circulation of water.

> (…) these kinds of displacements are true crevices that cross the layers of the soil to indefinite depths, almost always filled by surface detritus and, in many cases, acting as water sinks (Ribeiro 1854: 5).

Reassuring the Municipality about the location where the dam was to be built, Ribeiro reported that loose and thin elements formed a natural cement with the clays and filled the fractures, preventing the escape of dammed water. A layer of alluvial sediments had also been deposited above these materials. From his observations, he also found that the rocks outcropping at the bottom of the future dam area were saturated fine clay-rich sandstones, thus the water would be retained, even in the summer, thereby concluding: "(…) I have no doubts about the impermeability of the bottom of the river (…) the reason the site indicated by Pezerat is adequate" (Ribeiro 1854: 6).

Also concerned with the water quality, he drew attention to the needs of hygiene and health; however, he did not believe that the purification of water by resting could solve all of the problems, as this only enabled the settling of the heftier bodies in suspension and failed to take away the bad taste caused by the decomposition of organic matter. In this sense, he recommended the use of gravel, sand, or charcoal filtration, as had been successfully deployed in other European cities, or the construction of filtering galleries,[7] as Pezerat had also suggested.

The report, delivered on April 9, was commended by the City Council, which underlined its development "concerning the nature, extent and form of the soil," and awarded him the sum of £ 20, not as payment, but as recognition of merit (Monteiro 1854).

4 The Times of the "*First* (Water) *Company*"

Even though the reinforcement of the water supply to Lisbon had been politically defined in 1852 (Schmidt et al. 2005), its practical effects only materialized later, due to the *cholera morbus* epidemics of 1853–1856, impacting dramatically on Portugal, as well as throughout Europe.

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[7] This procedure was developed at the beginning of the nineteenth century by the Scottish engineer Robert Thom (1774–1847) and was used in river waters for human consumption in the city of Paisley, before becoming generalized soon afterwards.

By 1855, some Portuguese capitalists, who founded the “Waters of Lisbon Company” (known as the “first Company”), presented a proposal to the Municipality that aimed to provide a daily volume of water of 11,300 m^3 and that featured the construction of a network of tanks and conduits for distribution within the city. Water for irrigation, public baths and the fire service would be provided to the Municipality free of charge (Pinto 1989).

5 A French Expert: Louis-Charles Mary

Aware of its responsibilities, the Company was fast to engage a renowned technician to prepare the preliminary studies and project for the necessary works. On the suggestion of the engineer Vitorino Damásio (1807–1875), a professor at the Polytechnic Academy of Oporto who was visiting Paris, they contacted Louis-Charles Mary (1791–1870), an inspector of *Ponts et Chaussées* of Seine, who agreed to travel to Lisbon to analyze Pezerat’s proposals and visit the prospective collection areas. Nevertheless, he warned that he was not fully informed about the specific circumstances of Lisbon and, as such, he could only recommend the application of solutions already used in his country (Pinto 1989).

The overall contours of Charles Mary’s project were only adequately disclosed recently (Ramos 2011), in keeping with the failure of its primary goal: the effective reinforcement of the water flow to the city. This is ironic, as he was a critic of the Águas Livres Aqueduct, believing that it had been a huge and expensive construction that was concluded without any careful measurement of the volume of the springs collected in the Carenque valley. Serafim (2007: 75) then contradicted his opinion, stating that “countless surveys were made to ensure that the water was strictly measured” to justify such a costly work. He furthermore added (*apud* Ramos 2011) that, despite its “colossal dimensions,” the gallery only allowed for the drainage of small volumes of water and wasted the surplus in times of heavier flows (Fig. 3).

As detailed by Costa and Vital (2005), Mary outlined an extensive plan for the city’s supply, aiming both to pipe water into households and increase the production capacity of the Águas Livres Aqueduct. Contrary to the trend in other European capitals, he did not propose any recourse to steam engines, but rather the construction of cast iron siphons and the usage of the principle of communicating vessels to supply some reservoirs and fountains.

The project that the French engineer presented to the Company aimed at collection of the water that issued abundantly in the Vale da Mata (northwest of Lisbon) and its adduction through an 8600 m long aqueduct connected to the main Águas Livres facility. When the water arrived at the city, it was then distributed to the galleries and the Amoreiras reservoir, feeding large deposits, each with its own distribution network, and serving different altimetric zones (Mary, *apud* Ramos 2011), a pattern that was fully adopted by the Company and which is still in effect nowadays, alongside the necessary adjustments. Despite its optimistic solution, the

Fig. 3 Main aqueduct gallery depicting the water circulation gutters on each side of the central walkway. *Photo* courtesy of Pedro Inácio, 2010

project for the new subsidiary Mata aqueduct was received with apprehension by the municipal technicians, who stressed that it was only enough for the immediate satisfaction of the Company's needs, without offering any guarantees that it could actually fulfil the contract.[8] This concern soon became a reality when the summer water flow failed to exceed 500 m^3/day, producing an amount far less than what was expected, in a failure that led the government to rescind the contract and ascribe control of the urban water supply to the Municipality (Companhia 1900).

6 A "*Book of Science and Consciousness*"

Meanwhile, the Company's board of directors called Ribeiro into clarify several doubts that had been raised by Mary's project, requesting an opinion on the hydrogeological potential of Lisbon's surrounding area. He answered with a detailed geological field reconnaissance in which he described and mapped the main stratigraphic units over a topographic background drawn from the orographic map.[9]

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[8] Opinion report of the Municipality, cit. in Ramos (2011: 71).

[9] Carte chorographique des environs de Lisbonne dressé sous la direction de Charles Picquet à Paris, 1821 (Ribeiro 1857).

While the chief purpose involved identifying the geological formations with higher aquifer potential, considering their distance to Lisbon and altitude so as to minimize the adduction costs and avoid the costs of steam power for raising water, his report reached far beyond everything that had been previously produced, specifically by Daniel Sharpe (1806–1856).[10] This document was published by the Royal Academy of Sciences of Lisbon in 1857, of which Ribeiro had been a full member since 1854.[11]

The quality of the observations and the results verged on those of the finest publications made at the time, especially by French and British authors. These were not limited to the regional morphology and stratigraphic description, but also focused on the lithologies and the structure of the rocky massifs that essentially controlled the water circulation within aquifers. This important document reflects not only the reputation of its author, who was scientifically up-to-date, but also the confidence of the Authorities and the Company in national scientists, in addition to the author's determination to provide a geological survey prior to establishing any efficient water supply plan.[12]

> …[without] this geological reconnaissance (…) it is not possible to understand the principles on which the exploration and acquisition of potable water should be based, in order to determine the locality or localities that can provide more quantity of them (Ribeiro 1857: 34).

The results of these fieldworks were summarized in the chapters Geology and Hydrology, in which Ribeiro proposed a stratigraphic and structural model of the regional units ranging from the Cretaceous to the cover deposits, including the volcanic layers, to which he added the main details of the orography that were fundamental to understanding the hydrographic network patterns.

In his opinion, the geological structure of the area was quite complex when compared to other "basin types" of the same age, in particular, that of Paris, where a remarkable regularity of forms and the definition of the "geognostic" horizons facilitated their study. Conversely, "the inner forces of the globe" had exerted their actions around Lisbon, disturbing the composition of the rocks and "disrupting" the continuity and uniformity of the beds, producing the consequent rugged orography (Ribeiro 1857: 25).

The main local Cretaceous units recognized by Ribeiro, reformulated in 1867 and 1881, represented an important foundation for several subsequent works and were widely used for new stratigraphic precisions. They consisted of six "andares," with marine carbonate formations interbedded with two alluvial units of coarse sandstones showing good aquifer properties (Fig. 3). Among these, the "Primeiro

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[10] This British citizen was a pioneer of Portuguese geology and the president of the *Geological Society of London*. He met Ribeiro during fieldworks conducted in the Carboniferous units of Buçaco for the company Farrobo & Damásio. His publications about the region of Lisbon included a coloured geological map and a stratigraphic setting with several Jurassic and Cretaceous series.

[11] Lisbon Academy of Sciences, individual process.

[12] The accuracy of Ribeiro's geological observations was largely proven more than two decades later, when the first monograph by Choffat (1885) on the Cretaceous stratigraphy of Portugal was published, mostly with data yielded from the region of Lisbon.

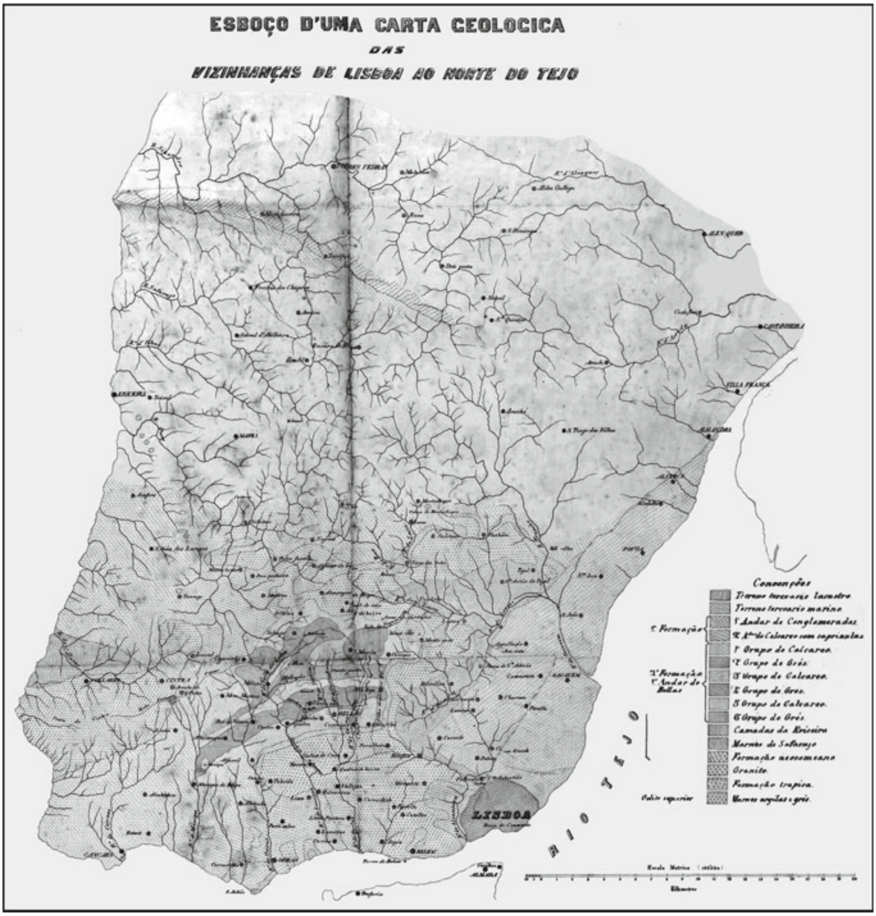

Fig. 4 Extract of the geological map of the peninsula of Lisbon by Carlos Ribeiro, published in 1857 by the Royal Academy of Sciences, Lisbon, and a detail of the main aqueducts, after Ferreira (1981)

Andar de Grés" (Ribeiro 1857) stood out, a sandstone formation later redefined by Paul Choffat (1885) as the "Almargem Beds" (Fig. 4).[13]

> Les grés d'Almargem ont une grande importance comme niveau aquifère; c'est d'eux qui provient une grand partie de l'eau qui alimente Lisbonne, c'est aussi de ces grés qui proviennent la majeure partie des sources minérales des environs de Bellas, Caneças et Cascaes (Choffat 1885: 5).

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[13] Its type of locality was in a tributary valley of the Carenque stream, crossed by drainage galleries later excavated under the direction of Ribeiro, where he also collected fossil plants that were studied by the Swiss paleobotanist Oswald Heer (1809–1883).

He was certainly faced with a large number of tectonic structures affecting the region, many of them active during the Late Cretaceous intrusion of the ring-shaped igneous massif of Sintra, the extrusive episodes of the Lisbon Volcanic Complex or, more recently, the Miocene compressive phases of the Lower Tagus Basin (Pais et al. 2006). Perhaps the most influential tectonic structure for the hydrologic purposes of Ribeiro was the reverse NNW–WSW fault located northward from Belas and intercepted by the Carenque stream, conditioning a north-eastern block where the "Almargem Sandstone" outcropped extensively and concentrated the aquifers and springs flowing into the aqueduct.

The lithological study and analysis of the structural setting, including stratification, diaclases, faults and igneous dykes, allowed him to evaluate the relationship between precipitation and the absorption area of the basins and aquifers, positioned below the drainage level of the land, as determinant factors for the location and architecture of the future collection system.

Following this methodology, Ribeiro concluded that none of the streams from the eastern side of Lisbon, which flowed into the Tagus River, with their beds carved into "Tertiary" sedimentary formations, could retain their surface waters. The geological reason for this insufficiency stemmed from the central and eastern zones of Lisbon having grown over a thick succession of Miocene marine sediments organized in tabular strata that dipped slightly into the river, with fine permeability qualities due to the presence of unconsolidated terrigenous lithologies (the "absorbing nature of the rocks," as Ribeiro put it, 1857: 37). This geological framework was also unfavourable to substantial collection levels, due to the absence of impermeable layers or structural traps for retaining groundwater. Thus, in his opinion, it would be impossible to obtain the rainwater received by these layers at higher levels, unlike from the dug wells situated lower, close to the level of the Tagus. Furthermore, for an absorption surface of more than 200 km^2, Ribeiro estimated that it would be possible to obtain at least an approximate 11,000 m^3 per day by taking advantage, through a gallery, of the waters otherwise lost to the Tagus.

The hydrological conditions became more favourable in the western part of the city, especially from the Alcântara valley onwards, due to the prevalence of deformed and fractured Cretaceous calcareous units, sometimes interbedded with permeable sandstones, alongside other areas covered by basaltic lava flows and tufts:

> It is to this physical and geological constitution that Lisbon owes its abundant sources of the eastern quarters, as well as the dryness and sterility of its soil in the high, middle and western parts; as a result of such inequality and scarcity, the public administration was forced to make recourse, in the past century, to the sources of the suburbs of Lisbon, to avoid the horrors of the thirst that the inhabitants of the capital suffered for centuries (Ribeiro 1857: 33).

Ribeiro strongly criticized the layout of the Mata aqueduct planned by Charles Mary. He opposed the project and stressed that, although the rainwater-receiving basin connected to the aqueduct spanned an area of about 16 km^2, there were large volumes of limestone with unfavourable hydrogeological conditions. In addition to those constraints, the upstream space was cut by "folds and valleys" in which the waters converged, limiting the amount that reached the aqueduct, which only received water from those springs located above its planned altitude. There was also the fact that the water contained in the four main springs, which reached over 7300 m^3/day in June 1856, came from different layers (aquifers), functioning independently, which did not ensure stable water flows, due to their different recharging speeds.

According to the lithology and structure of the massif drained by the Mata aqueduct, Ribeiro estimated a collection capacity of about 5800 m^3/day, which, combined with the flow from the Águas Livres Aqueduct, would still not reach the volume of 11,300 m^3 per day proposed by the Company. To obtain this volume, it was necessary to reinforce the main structure with subsidiary galleries and collecting pipes, covering an estimated area of about 10 km^2, to capture other springs, as, due to the topographic level at which the work was planned, a large volume of water from the lowermost aquifers would not be used.[14]

Inspired by the examples of French authors such as J. Dumas and Polonceau, experts in the field of "*la science des fontaines*," Ribeiro suggested some redemptive strategies for increasing the efficiency of Mary's aqueduct, improving the absorption of rainwater and the volumes retained in the aquifer. These included the planting of woods on the ridges, hill slopes and stream banks and the opening of trenches along the contour lines in the areas where there were sandstone outcrops, in addition to applying the "natural fountains" method, in which a network of ditches with dry stone walls and impermeable bottoms were opened and filled with loose soil, mutually interlinked and draining into regulatory basins (Ribeiro 1857).

As an alternative to the Mata aqueduct, Ribeiro recommended the exploration of waters near the locality of Belas and the construction of a further collector, the Agualva aqueduct, at a level higher than Mata. This structure was planned to cross several streams where groundwater converged and, running approximately 2.5–3 km in length, would provide about 9000 m^3/day in the dry season and up to 24,000 m^3 during winter, due to its larger rainwater absorption surface, taking advantage of the better hydrogeological conditions, with a bedrock composed of limestone and marly layers interbedded with sandstones and claystones, dipping towards Lisbon.

Although solidly based on geoscientific data, Ribeiro's suggestions were ignored, and Mary's project, as well as its budget, was approved by the ordinance of June 30, 1857. Ribeiro nevertheless continued to believe that the aqueduct planned by Charles Mary was doomed to failure. In his opinion, if the Company did not take advantage of the waters of the Eastern Quarter (lower quality but potable),

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[14] Ribeiro also mentioned the scope for taking advantage of sources from the eastern quarter of the city, sources that were inferior in quality but drinkable, as had been previously suggested by Pezerat. The surplus water from these sources flowed freely into the Tagus River until 1868, when the Praia Elevatory Station, the first steam pumping station installed in Lisbon, entered into operation. This new station was able to pump about 1800 m^3/day to the middle areas of the city (Bruno and Inácio 2014).

in the short term, it would be obliged to undertake new works or build another aqueduct as large as or even larger than Mata to collect other springs. In addition, Ribeiro pointed out that the short time that the French expert had spent in Lisbon was not enough for detailed observations; he had merely accepted the hypothesis of a certain volume of water in each of the sites visited, proposing its collection and adduction without truly guaranteeing its success (Ribeiro 1857). This position might be perceived as an act of professional loyalty, as emphasized by the columnist of the popular Lisbon weekly newspaper *Archivo Pittoresco* (1857), since Ribeiro reiterated his conviction that Mary had been faced with a very tight deadline. For this reason, the columnist called Ribeiro's report "a book of science and consciousness" (p. 110). However, Ribeiro still warned:

> The contempt for the study of the lithological composition and structure of the soils where water exploration, hydraulic or other works are going to be carried out, is often the motive of the best combined projects to fail (Ribeiro 1867: 111).

7 The Solution: Spring Waters *Plus* River Waters

In January 1863, the Company presented new water supply plans designed to meet the growing needs of Lisbon, including usage of the wells available within the city and the exploitation of sources from the eastern quarter. They also pointed out the scope for drawing water from the Tagus River, sent to the city through a buried siphon and raised to an appropriate topographic level, making its distribution possible in the higher urban areas (Pinto 1989).

Despite these (late) proposals, the government decided to cancel the concession, on the grounds that the company had failed to meet the contract and the government's lack of faith that the Tagus's ability to supply water was a proper solution (ordinance from October 7, 1863). Simultaneously, an evaluation committee was appointed, with the participation of Carlos Ribeiro as an expert in hydrology and regional geology. The objectives were for its members to determine how much water the Company could efficiently provide to the population in the dry season, to present a detailed technical opinion about the system's future, specifically, through an inventory of the availability and quality of new water resources, and to determine the most convenient and cost-effective ways of bringing them to Lisbon.

The work carried out and presented to the government in 1864 gave rise to an extensive "Memoir," published by the Geological Commission in 1867, in which Ribeiro analyzed each of the projected and delivered parts of the system, setting out his criticisms and suggestions, and explained his ideas about the use of river waters, deploying the situations reported by French and British authors as examples.

In this notable work, fully commented upon by Simões (2013), Ribeiro bore in mind all of his previous observations on the regional geology, namely, the distribution of the most permeable Cretaceous sandstone beds and limestones, faults and basaltic dykes that cut the sedimentary succession (Fig. 5). He also provided advice

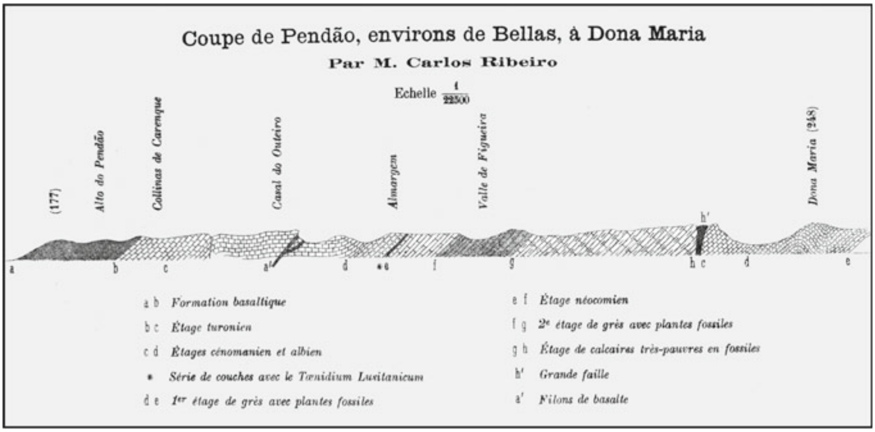

Fig. 5 Geological cross-section by Carlos Ribeiro, portraying the regional Cretaceous units, dykes and main faults. Rep. from Oswald Heer, 1881

on the conclusion of works on several Águas Livres Aqueduct subsidiary structures, as well as the extension of the Mata aqueduct, whose efficacy had previously been received with great apprehension.

Furthermore, he pointed to the substance of Pezerat's proposals in also suggesting that the capture of all of the spring waters was feasible for introduction into the aqueducts, as well as those from the eastern zone and other sources within the city. However, he was concerned, not only with the quantity of water to be supplied, but also its quality.

At the time, the idea of water as a privileged vehicle for the spread of pathogens had not yet been consolidated, even though it was known that water collecting near sewage and waste disposal sites constituted a high risk to public health. Since the Renaissance, water quality had been evaluated based on a series of empirical criteria: its smell, taste and appearance, its clearness, the absence of suspended matter, and its quality for culinary uses (Euzen and Haghe 2012; Sowina 2016).[15]

In addition to clearness, Ribeiro said that potable water should present at a nearly constant temperature, be odourless and pleasant to the taste, and be suitable for cooking vegetables and dissolving soap thoroughly. The substances in the solution should not exceed 300 mg/l, nor should organic matter be present in any appreciable quantities. Finally, the water should not register more than 24 °C in the hydrotimeter.

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[15] An early example concerning the Lisbon water supply regards the Portuguese pioneer of hydraulic studies, Estevão Cabral (1734–1811), who pointed out the need to end the aqueduct at the reservoir of "Mãe de Água," because the water did not arrive "clean" due to the absence of a tank that could provide for the sedimentation of the suspended matter, by which it would be "purifying itself." He believed that the dissolved salts could also precipitate there, instead of inside of the pipes, where they caused serious damage to the runoff (Cabral 1791).

One part of these characteristics not only directly related to the crossed lithologies, but also to the time and distance that it took the water to flow into the ground. To ascertain this situation, Ribeiro sampled the main fountains of Lisbon,[16] in a way that revisited certain aspects of a study carried out in 1812 by the naturalist Alexandre Vandelli (1784–1862), who sampled the main springs, mines and dug wells that were in use by the population. He measured the temperatures of the water and the atmosphere and determined the values of density according to the content of dissolved substances, before concluding:

> On account of water that weighs less being more profitable in the *animal economy*, since the number of dissolved heterogeneous bodies is smaller, those of smaller specific gravity must be chosen for economic usage (Vandelli 1812: 81).

The samples that Ribeiro collected in January 1864 were analysed by the chemists of the Polytechnic School of Lisbon, António Augusto de Aguiar (1838–1887), also an influential politician, and Júlio de Oliveira Pimentel (1809–1884), who characterized the dissolved substances and the hydrotimetric degree, taking as his default the values for the best water quality proposed by French hygienists: a hydrotimetric degree of between 8 and 18 and with a salt content of between roughly 100 and 300 mg/l.

Their results showed significant differences between the waters sampled from different points of Lisbon, both in their salt content due to rainfall variations and lithology, according to Ribeiro's opinion, and in hydrotimetric degree, which varied between 17.5 and 35.5, with a single anomalous value of 66. As for salt content, Júlio Pimentel found values of between 562 and 749 mg/l in the main Eastern Quarter fountains, much higher than those found in the aqueduct water, 277 mg/l, a fact interpreted as a consequence of a shorter underground pathway. If these more mineralized waters from the Eastern Quarter were to travel along an underground route for as long as those collected by the aqueduct, "they would purify, reaching consumers with less dissolved salts" (Ribeiro 1867: 12).

It should be added that those waters sprang at an average temperature of over 22 °C, which, combined with their high mineralization, indicated a thermal origin. In any case, based on the examples of the foreign scientific literature and the experience of Portuguese hygienists, Ribeiro recommended their usage, given the constancy of flow and the clearness of their springs.[17]

Considering the rapid changes in the consumption habits of the population and matters of urban hygiene, as well as the amount of water available per inhabitant in many foreign cities, Ribeiro estimated that Lisbon, with nearly 200,000 inhabitants

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[16] Attached to Ribeiro's (1857) report, there is an extensive inventory of the fountains, wells and other water sources of Lisbon, which support his conclusions.

[17] The physician Bernardino Gomes, a notable figure in Portuguese medicine in the nineteenth century, recommended that his patients consume water from one of these fountain systems, El-Rei, instead of the water arriving via the aqueduct (Ribeiro 1867: 16). However, after being chemically and bacteriologically analysed in 1890, the "eastern waters" were classified as being of mediocre quality, considering their high mineral content, as well as their contamination with colibacilli, possibly due to poorly constructed sewers. Its consumption had been abandoned by the 1930s (Companhia … 1900).

at the time, would require a volume of at least around 150 l/day/hab. (p. 36), an amount that would need to be increased in the future, assuming that the population of Lisbon would double or triple over the subsequent fifty years. The author's substantial knowledge on the geology of Lisbon and its neighbouring areas gave him the authority to assert that the region was far from being able to supply the capital's future needs, even considering the scope for using all of the springs identified within the city and near volcanic rocks, dikes, faults and Cretaceous sandstones.

The methodology presented in 1857 proposing the excavation of wells or galleries to capture the subsurface waters along the valleys and streams had only been deployed in isolation for the supply of a few large cities (Ribeiro 1867: 21). These more populous areas demanded the search for new perennial and abundant sources, and the eventual combination of different supply systems, depending on the geological nature of the bedrock. To solve this problem, he proposed deep collection in confined aquifers, as was practiced in Liverpool, and/or the exploitation of river waters purified by filtering galleries, as was then happening in London and Paris.[18]

To this end, he studied water samples collected in the Tagus approximately 100 km upstream from Lisbon, beyond any tidal influence, between the riverside localities of Santarém and Barquinha, subject to analysis by Augusto de Aguiar. Through his methodology, he sought to determine the relationship between the lithologies of the river banks, the amount of dissolved substances present in the water and the season of the year (Table 1), concluding that its maximum proportion occurred during the dry season, and that the concentration of dissolved salts was higher in the Tagus River sections where there were debouched tributaries with larger drainage basins rich in limestone and sandy-claystone lithologies (Ribeiro 1867).

Despite the oscillations recorded, the amount of "fixed materials" contained in the waters of the Tagus was lower than that found in some of the spring waters collected by the Águas Livres Aqueduct[19] and compatible with the limits suggested by the hygienists, thereby fully satisfying the Company's commitments (Ribeiro 1867). However, these values did not invalidate the need for natural or artificial filtration, for which Ribeiro relied on examples of successful experiences abroad, specifically, in France, the United Kingdom, Austria and Germany, including the scope for using coarse alluvial deposits from river bars as the means of ensuring natural filtration. Subsequently, he studied the Quaternary sediments of the Tagus River basin, northeast of the city, before concluding that the natural filtration of sand and gravel banks and the capture of deep circulation "artesian waters" represented a feasible option.[20]

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[18] In the Portuguese cities of Coimbra and Oporto, waters from the Mondego, Douro and Sousa Rivers were already in use for public supply.

[19] In February 1864, the water from the Aqueduct was reported as 16 °C on the hydrotimeter, with 0.293 g/l of residuals (Ribeiro 1867: 43).

[20] After 1935, the Company reinforced the Lisbon supply with several underground water holes drilled into the Tagus River alluviums (naturally filtered waters) on the sites studied by Ribeiro.

Table 1 Results of the analysis of Tagus and Zêzere River waters, collected in 1863 and 1864

Sampling station	During the dry station	February, after the rains	
	Hydrotimetric degree	Hydrotimetric degree	Fixed residuals (g/l)
Tagus River waters collected in front of Barquinha	23	14	0.192
Tagus River waters collected in front of Santarém	24	16	0.238
Tagus River waters collected in front of Constância	16	19	0.268
Waters from Zêzere[a] mixed with those of the Nabão River	16		
Waters from Zêzere collected upstream the mouth of the Nabão	2.5	4	

Following Ribeiro (1867)

[a] The Zêzere is one of the main tributaries of the Tagus River. Its waters have also been collected since 1987

In sum, Ribeiro came to the view that, based on his detailed study of successful foreign cases, the overall solution for the supply of large settlements would involve the usage of Tagus waters captured upstream, far from the tidal influence or contamination by sewage and duly purified by natural or artificial filtration. However, should this recourse to river waters be rejected, the city's supply would have to be guaranteed by spring and drainage waters.

> (…) the men of sciences and the administration, when occupied with the acquisition of new spring waters for this purpose, should be obliged to leave their observations from the suburbs of Lisbon and to lengthen them many tens of kilometers to the north and northeast areas of the city (Ribeiro 1867: 64).

Ribeiro extended his studies 100 km further northward of Lisbon, to the calcareous mountain ranges of Montejunto and Aire, where perennial sources were present in the Jurassic limestones, near the localities of Rio Maior, Ota, Alenquer and Alcanena.

In spite of the distance and the higher costs of an adduction system, the vast spring of the Alviela River, known as "Olhos d'Água," undoubtedly represented an interesting possibility. This was a singular site, about 60 m above sea level, located in the intersection of two major faults, with a flow of over 200,000 m^3 of water per day, most of which proceeded freely into the Tagus River. Nevertheless, Ribeiro argued that the Alviela River was also being used by more than twenty mills along its course, which would have to stop in the dry season should the water be diverted to Lisbon, therefore advocating its usage for agriculture rather than for local consumption. Nevertheless, he suggested that nearly 30,000 m^3 per day could be sent to Lisbon without any considerable impairment on traditional uses.

However, bringing in the waters from Alviela required a greater investment than the Municipality could afford. This thus became an opportunity for the private investors who, in 1868, formed the Companhia das Águas de Lisboa (Lisbon Water Company), which still stands today, despite having undergone several transformations.[21]

8 Old Plans for New Waterworks

The year of 1874 was hard for both the Company and the population, due to a long drought that drastically diminished Lisbon's water supply. The Government commissioned Ribeiro to urgently implement a solution to reinforce the supply to the Mata and the Águas Livres aqueducts. It was requested that he source drinkable water as quickly as possible, and for the works carried out to be useful over the long term. At this time, when commenting on the situation and blaming the great water shortage in Lisbon for its effects on food and hygiene as the cause of the "plagues" that had devastated the capital, he said:

> (…) for more than twenty years Lisbon has been fed less than one-tenth of the water that is considered indispensable for its supply as the capital of a cultured nation; (…) the hygienists and the statistics have cried out that, for this reason, in Lisbon you breathe a pestilent and mortiferous air (Ribeiro 1879: 408).

With the collaboration of Nery Delgado, Ribeiro began exploring the Cretaceous layers of the Almargem sandstones, outcropping near Belas, Sabugo, Brouco and Vale de Lobos, in the intersection of three valleys located upstream from the Mata aqueduct, layers that he had first found during his fieldwork in 1857. He led expeditions into the limestone formations, as these lithologies were quite cavernous and permeable and, as such, the waters of the upper regions disappeared into them, hence the need to reach lower depths to find the confined aquifers (Ribeiro 1879). In order to extract more water, wells were excavated to depths of between 20 and 30 m, making it necessary to use a Letestu pump system driven by a locomobile to raise the water. More than 100 wells were opened, and new aqueduct branches built, allowing for the minimum collection of 400 m^3/day (Fig. 6). Although these works had to be extended in mid-1885, already under Delgado's direction, when the government decided on their temporary suspension in 1878, they could yield about 720 m^3/day (Company … 1900), a flow that mitigated the effects of the drought.

After the first works, Ribeiro sent a report to the Government reiterating that the higher relief areas in the vicinity of Lisbon contained a geological composition and structure that might contribute to increasing the city's water supply, even if,

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[21] By 1868, Lisbon was served by several private wells and cisterns, 26 springs and 97 water spouts supplied by the aqueducts and scattered across various points of Lisbon, of which 48 were used by 3129 water carriers and 40 by private customers, with 9 reserved for the filling of barrels (Ferreira 1981: 130).

Fig. 6 **a** Detail of the system of galleries located near Belas; **b** vents from the underground captation galleries. *Photos* courtesy of Pedro Inácio, 2010

however, they was unable to provide a long-term supply on their own. Nevertheless, were his plan for the Agualva aqueduct and collection in the eastern part of the city to be executed, the Company would then have more than 14,000 m^3/day, surpassing the contracted flow:

> One of the causes that contributed most to the subterranean exploration work we indicated not being carried out (…) was the lack of faith, the lack of confidence that the exploration of drinking water by works of that nature could have inspired in so many enlightened people. Drinkable water cannot be obtained in abundance by means of underground work, even if it penetrates deep (…) in any and all geological formations; it is necessary to study and to know well the physical structure and the lithological composition of the soil of the region, and only then will it be possible to indicate the probability of finding or not finding more or less rich springs (Ribeiro 1879: 480).

While these works were ongoing, the Alviela channel was also constructed and the equipment needed for the reception and steam elevation of these waters underwent preparation.

The abduction of the Alviela waters followed a gravity flow process through underground and surface conduits, alongside two main siphons to overcome the biggest orographic accidents, installing cast iron pipes at that time manufactured by the main Portuguese foundries. This procedure was also used in Delgado's water supply project for Figueira da Foz, which was proposed to the Municipality in 1880 (Brandão and Callapez 2017). That same year, the Barbadinhos steam pumping station, built in the heart of the Eastern Quarter, was inaugurated, bringing a volume of water to Lisbon that was compatible with those of other major foreign cities (Table 2).

Table 2 Availability of water in the city of Lisbon

Year	Sources	Population	m^3/day[a]	l/inhab/day
16th century	Fountains, springs and dug wells	60,000	200 to 300	4.0
Early 18th century	Idem	80,000	540	6.0 to 7.0
1748	Idem plus water from the Águas Livres Aqueduct	90,000	780	8.4
1863	Idem plus water from the Mata and Brouco aqueducts	160,000	2360	14.7
1869	Idem plus water from the Francesas aqueduct and waters from the Lisbon Eastern Quarter	171,000	4280	25.0
1874	During the great drought		1663	
1878	After Ribeiro's works in Belas	187,000	5000	26.7
1880	Arrival of the water from the Alviela river	191,000	35,000	183.2

Following Ribeiro (1879), Montenegro (1895), Companhia … (1900)

[a]The numbers are somewhat discrepant among the authors consulted

9 Final Remarks

Even though the construction of water supply systems for human consumption has been a concern ever since Antiquity, urban networks for water and sanitation only gained momentum in the aftermath of the Industrial Revolution. Despite the importance attributed to fire safety, public health issues were decisive in the replacement of traditional water supply systems, based on dug wells and cisterns, with modern collection systems, which ensured the quality of the water delivered to households. London was a pioneer in this process, both from technological and organisational points of view (Juuti and Latko 2005; Tynan 2013; Matés-Barco 2013; Gorostiza and Cubero 2013).

Notwithstanding its character as a natural monopoly, water supply is mainly a local issue. Traditionally, this was provided for by local authorities, who managed their own systems during the nineteenth century. Many cities conceded this service to private operators, believing that they could handle the waterworks better than the municipalities and that they would bring investments and innovation. This process was soon reversed, primarily for reasons of public health or contractual inadequacies (Juuti and Latko 2005).

In Portugal, during the second half of the nineteenth century, under a new legal framework regarding property and the usage of water resources, several companies were also established, promising significant financial and technological innovations and aiming to operate the water supply systems under concession. However, the fact that water became a business did not prevent a set of positive externalities, particularly regarding public health and urban hygiene. The founding of companies that provided water exploration and distribution in Portugal resulted from this paradigmatic change. Nonetheless, it should be noted that, besides foreign technology, imported for the construction of larger waterworks, the Lisbon Water Companies also resorted to national technicians whenever it required the expertise of state geologists, particularly members of the new Geological Commission, who were informally consulted on matters related to mineral raw materials or public works and infrastructures.

In contrast to the traditional methodologies, which were mainly based on the use of surface springs and the topographic and altimetric features of water basins, the precursor works of Carlos Ribeiro in Lisbon, besides considering the hydrological cycle, involved understanding the mechanisms of groundwater circulation, their dependence on the lithology, structure and seasonal rainfall fluctuations, and the chemical and physical properties of water. These matters, which constitute the main principles of "ground-water hydrology," as James Hackett mentioned in his "summary" on the birth of this branch of geological study (1952), were also the guidelines that Nery Delgado and Paul Choffat followed. In virtue of their expertise in geology and engineering, they too were requested to issue their advice on identical situations in other Portuguese cities.

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