



# The “Sete Fontes” groundwater system (Braga, NW Portugal): historical milestones and urban assessment

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## Abstract

Water resource assessment is essential to bring about sustainable growth of urban development and overall economic progress. Climate change and population growth pressure are important drivers in the available water resources. The crucial point of water management should be to promote an integrated water management in a river catchment and associated groundwater systems. The ancient drinking water system from Sete Fontes (Braga, northern Portugal) was built in the mid-eighteenth century, and was the main water supply system of the city until 1913. This water system is located in a valley, with a NE–SW trend, promoting a favourable gentle slope to water–gravity transport into the city. The Sete Fontes aquifer is characterized by Silurian metasediments intruded by Variscan granites, with two main fracturation trends—ENE–WSW and NW–SE. The main hydrogeochemistry composition is Na–Cl facies and locally Na–HCO<sub>3</sub> facies. The groundwater is poorly mineralized, suggesting meteoric water contribution, with a relatively shallow circuit. During the Roman period, Sete Fontes system was probably the main source of water for the city. The economic, and demographic expansion of Braga lead to the increasing use of other water resources. Presently, the city’s primary delivery system is only the surface water supplied from Cávado catchment. Natural groundwater characteristics from Sete Fontes show that it is still suitable for human consumption and also for non-potable uses. The assessment also suggests that this is a sustainable water resource, that can constitute an important backup solution in case of failure of the main delivery system due to scarcity or catastrophe.

**Keywords** Urban groundwater · Hydrogeochemistry · Springs · Roman system · National monument · Braga

## Introduction

Water is a precious natural resource, essential for life on Earth. The availability of quality water is a basic requirement for economic and social development. Our everyday lives depend on the availability of inexpensive, clean water and safe ways to dispose of it after use. Water resource development is essential to bring about sustainable growth of urban development and overall economic progress (e.g., Bono and Boni 1996; Sharp 2010; Angelakis et al. 2012;

Margat and van der Gun 2013; Chaminé et al. 2014; Freitas et al. 2014; Chaminé 2015; Howard 2015). Moreover, climatic change and population growth, among others, are putting enormous pressure on the limited available water, in a growing number of regions of the globe. Nowadays, water concerns remain high on many national agendas, especially in developing nations, since past ‘compartmentalised approaches’ to water management have generally failed to achieve sustainable outcomes. (Foster and Ait-Kadi 2012; Ahamed et al. 2015; Howard 2015). The crucial point of water management should be to promote the integrated water resources management to maximize the resultant economic and social benefit in an equitable manner without compromising the sustainability of vital ecosystems (Mays 2010; Adeba et al. 2015; Afonso et al. 2016).

Water supply systems and morphology of ancient cities suggest a strong constraint between urban development and water sources. The availability and location of water resources are mainly associated with a possible transport to the populations. Groundwater provides an important

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source of water over much of the world, being the safest kind of water supply at our disposal, more convenient and less vulnerable to pollution than surface water (Hiscock and Bense 2014). Since groundwater normally has a natural protection against pollution by the covering layers, only minor water treatment is required (Kirsch 2006; Brassington 2007). Aquifers are not just sources of water supply, but also vast storage facilities that give us great management flexibility of groundwater resources at a relatively affordable cost (Foster and Ait-Kadi 2012; NRC 1994; Afonso et al. 2016). It is estimated that approximately one-third of the world's population uses groundwater for drinking purposes (WHO 2005; Sharma et al. 2012). The groundwater resources play a very significant role in meeting the ever-increasing demands of the agriculture, industry, and domestic sectors (Saleem 2007; Saba and Umar 2016; Gómez et al. 2017). Groundwater, because it is unnoticed underground, is often unacknowledged and undervalued, being under threat worldwide of overexploitation, land surface impermeabilization and contamination from a wide range of human activities. In many countries, activities that may have an impact on groundwater are regulated by government organizations, which frequently require hydrogeological investigations to assess the risks posed by new developments. It is crucial to evaluate groundwater quality, to ensure that it is suitable for drinking and for other uses, and to promote strategies to minimize risk of contamination (e.g., Brassington 2007; Ackah et al. 2011; Sayyed and Wagh 2011; Tiwari 2011).

The consumption of groundwater for various purposes such as drinking, domestic, agricultural or for industrial use is dependent on the chemical composition of groundwater, thus an understanding of the geochemical composition of groundwater is necessary for the sustainable development of water resources. The chemistry of the groundwater system of an area is unique and may be altered chemically depending upon several factors such as water–rock interaction, dissolution of mineral species and anthropogenic impacts (e.g., Subba Rao 2001; Umar and Absar 2003; Antunes and Gonçalves 2017).

Understanding the aquifer properties and hydrochemical characteristics of water is crucial for groundwater planning, protection and management in the study area. Groundwater chemistry depends on several factors, such as geological background, degree of chemical weathering of various rock types, quality of water recharge and inputs from sources other than water–rock interaction.

Urban hydrogeology could be defined as the part of hydrological cycle focused on groundwater processes, groundwater exchange and water quality in urbanized territory (e.g., Afonso et al. 2010; Chaminé et al. 2010; Foster et al. 2011; Hibbs 2016). The city of Braga (NW Portugal—Fig. 1) is, presently, almost entirely dependent on surface water from Cávado river catchment. Until the beginning of the twentieth century, as will be presented, groundwater was Braga's main source of water. Its water supply framework is similar to other Portuguese urban areas (e.g., Afonso et al. 2010, 2016 and references therein) (Chaminé et al. 2014;

**Fig. 1** Location of city of Braga

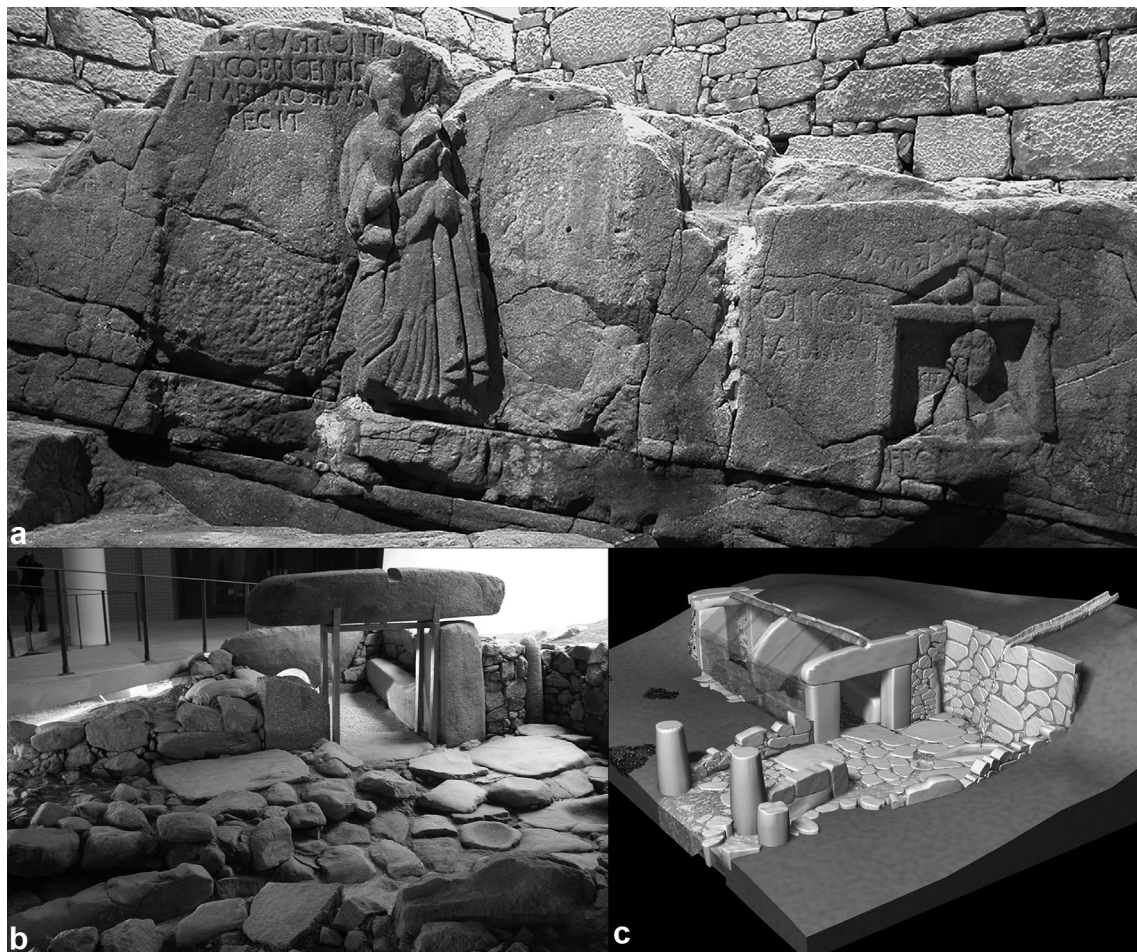


Freitas et al. 2014). In a scenario of water scarcity, associated with drought, catastrophe or other phenomena (related or not with global climate changes), the dependence of one single water source can compromise the delivery of water, with enough quality and quantity to meet the city needs. Old groundwater systems, such as Sete Fontes, can still be of great value, and it is of great importance to evaluate the water quality and to promote measures that can protect these resources. Moreover, it is of vital importance that groundwater of impaired quality remains an economically useful source, particularly well-suited for non-potable purposes, e.g., irrigation of parks, lawns and golf courses, street cleaning, car washing, fire fighting, and toilet flushing (Afonso et al. 2010, 2016; NRC 1994). In this research, the hydrogeological characterization of Sete Fontes aquifer will be integrated with water composition. It will be also address the associated cultural, social and historical relevance of this resource. This study aims to contribute to a sustainable water resource assessment, and to show the importance that Sete Fontes groundwater can still have to the city of Braga.

## Sete Fontes historical framework

### Pre-Roman era

Since proto-historical times, water has been important for the people who lived in the area that would become the city of Braga. Two particular places, considered by Colmenero (2015) as worship places, document well the strong relationship between pre-Roman populations and water: the Fonte do Ídolo (Idol Fountain) and the pre-Roman bath of the railway station (Fig. 2) (Lemos et al. 2003; Lemos 2008; Martins et al. 2011a, 2012). In the Fonte do Ídolo sanctuary, later monumentalized in the Roman period, water worship took place, being dedicated to the goddess Nabia and other local deities (Garrido et al. 2008; Colmenero 2015). The pre-Roman bath was identified in 2003, during preventive excavations within the city railway station refurbishment project (Lemos et al. 2003). The monument was found to be partially destroyed, but it was



**Fig. 2** **a** Pre-Roman sanctuary of Fonte do Ídolo; **b** pre-Roman baths from Braga railway station; **c** 3D reconstruction of the baths (adapted from Lemos 2008)



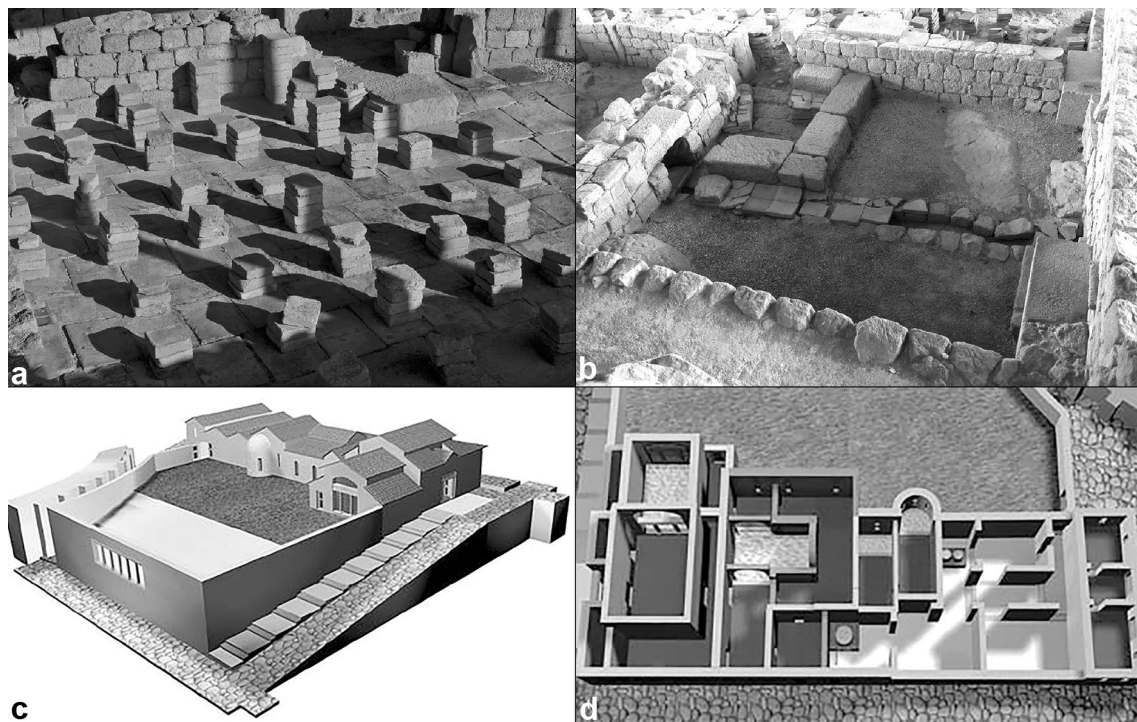
possible to reconstruct the structure that was composed of an oven, a steam chamber and an antechamber with side bench seats and accessed through a paved courtyard (Lemos 2008). This indigenous bath structure is common in the Iron Age hill forts of the region, and its primary function was to provide both cold water and steam baths, associated with religious and cultural practices that could be related with initiation rites (Martins et al. 2012).

## Roman period

A diverse archaeological heritage of the Roman city of Bracara Augusta (modern day Braga) is directly related to water, witnessing several aspects related to the ancestral drinking water and sanitation systems. This heritage documented by several authors (e.g., Martins 2000, 2005; Lemos 2008; Ribeiro 2008, 2010; Martins et al. 2011a, b, 2012; Ribeiro and Martins 2012; Teixeira 2012; Martins and Carvalho 2016), allows to fully understand the infrastructures constructed to manage and use water during Roman times. There is still much uncertainty, for this period, about the location of water sources and its abstraction points, either within the city or in the outskirts of the urban centre (Martins et al. 2011b, 2012). Bracara Augusta could not have survived without aqueducts, which were essential in supplying the large amount of water needed for both the public

(Fig. 3) and private baths that existed in different sites of the urban area (Martins et al. 2011b). It is presumed, based on archaeological evidences, that wells could have ensured water supply to the city on a first occupational stage after the foundation (16–15 B.C.) (Martins et al. 2011a). Nevertheless, the growth of the urban centre in the first and second centuries demanded more complex water-supplying techniques (Martins et al. 2012) and a more productive source with higher water quality. Considering the several archaeological evidences found in the city (Lemos 2008; Martins et al. 2012; Teixeira 2012) and in the outskirts (Braga and Pacheco 2013), and taking into account the number of public and private baths and other water-related public buildings, the existence of, at least, one aqueduct, which could supply water from outside the city, most likely from the Sete Fontes region is assumed, according to the morphological, hydrogeological and archaeological evidences (Lemos 2008; Costa 2012; Martins et al. 2012; Rodrigues 2012; Teixeira 2012; Vieira et al. 2016).

It is only known that some of the Roman aqueducts, that transported water to the city have remained active after the Suebi conquest in 409 A.D., although without proper maintenance, it led to their collapse in the early Middle Age, explaining some of the water shortage and public health problems in the city, often referenced in the historical documentation (Ribeiro and Martins 2012).



**Fig. 3** Bracara Augusta Roman public building from the Alto da Cividade (third century). **a, b** Perspectives from the archaeological excavations. **a** Praefurnium. **b** Apodyterium hypocaust. **c, d** 3D recon-

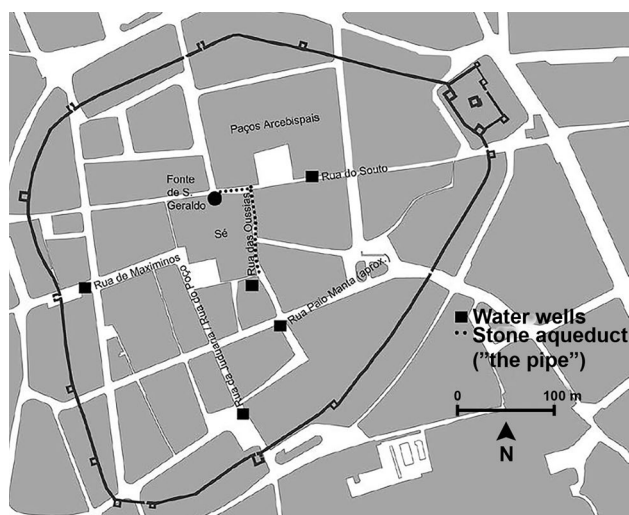
struction of the Roman Thermal building (adapted from Martins et al. 2011b; Martins and Ribeiro 2012)

## Middle age

With the end of the Roman domain, in the fifth century, the urban population reduced and some cultural and social changes occurred. These modifications converged in a reduction of the water consumption. Considering the size of the city in the High Middle Ages, and the collapse of the Roman water supply system, the intramural drinking water system should have been almost exclusively dependent on wells (Vieira et al. 2016). Some medieval documents reveal not only the concerns to improve the water abstraction capacity (looking up to new sources or returning to some already existing), but also real difficulties to face when the water demand increased in the urban centre, due to the Braga city's growth in the fourteenth century that implied the boundary enlargement of medieval rampart (Martins et al. 2011a).

Documents of the fourteenth and fifteenth centuries (Marques 1980; Ribeiro and Martins 2012) refer to several hydraulic infrastructures existing inside the rampart: nine wells (in six central streets), one stone aqueduct ("the pipe") and the (underground) Fonte de S. Geraldo (St. Gerard Fountain), with the locations shown in Fig. 4. One of these public wells (the southern one) remained operational until the nineteenth century and has constituted one of the most important sources of drinking water in the medieval town.

One interesting mention on historical documents, about the medieval water supply system (late fourteenth century), refers a "pipe" (of unknown origin, but with records on their restoration and enhancement works), which was even used as a reference for some of the major city streets. This stone aqueduct flanked the head of Braga Cathedral, near the Archiepiscopal Palace, aiming to supply the most

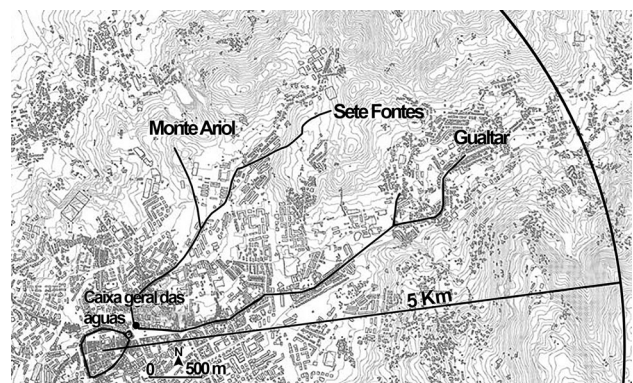


**Fig. 4** Location of some of the identified sources of water who supplied the medieval city of Braga (adapted from Ribeiro and Martins 2012)

important part of the medieval city, perhaps through the Fonte de S. Geraldo (Fountain of St. Gerard), and probably, in the Roman period, supplying a market (macellum), which would have required a large quantity of water (Fontes et al. 1998).

From the second quarter of the fifteenth century, these water sources (within the walls) demonstrated to be insufficient to meet the increasing water demand (Vieira et al. 2016). Therefore, it was necessary to reactivate old or find new sources on the outskirts north of the city but less than a land league (about 5 km) away (Fig. 5). From there, the water would be transported by covered stone aqueducts till the medieval city from where it should be distributed by different devices, like fountains, waterspouts, tanks, and washtubs (Marques 1980). Some of these aqueducts would probably be from the Roman period, as there are traces of them along the major Roman roads (Martins et al. 2011b), like Via XVIII (linking Bracara Augusta to Asturica Augusta—Astorga in Spain) or the Via XVII (linking Bracara Augusta to Aquae Flaviae—Chaves).

Since ancient times, it has been extremely important to ensure that water abstracted in remote areas could reach a main reservoir (called the matrix), from which water could then be distributed to different strategic distribution points within the city (Martins et al. 2012; Vieira et al. 2016). The Romans used a water reservoir (castellum aquae or castellum divisorium) that received water from aqueducts and then distributed to fountains and bathhouses covering different areas of the city. So, it is quite likely that a Roman castellum aquae could be in service in Bracara Augusta at the same location where in more recent times the main water reservoir of Braga, called Caixa Geral das Águas (Fig. 6), near the city walls, has been referenced. This main reservoir was a stone structure, located near the medieval rampart, which had in its interior a great arch for water entrance, perhaps to perform water aeration (Vieira et al. 2016).



**Fig. 5** Probable water supply zones for the "Caixa Geral das Águas" (adapted from Ribeiro and Martins 2012)



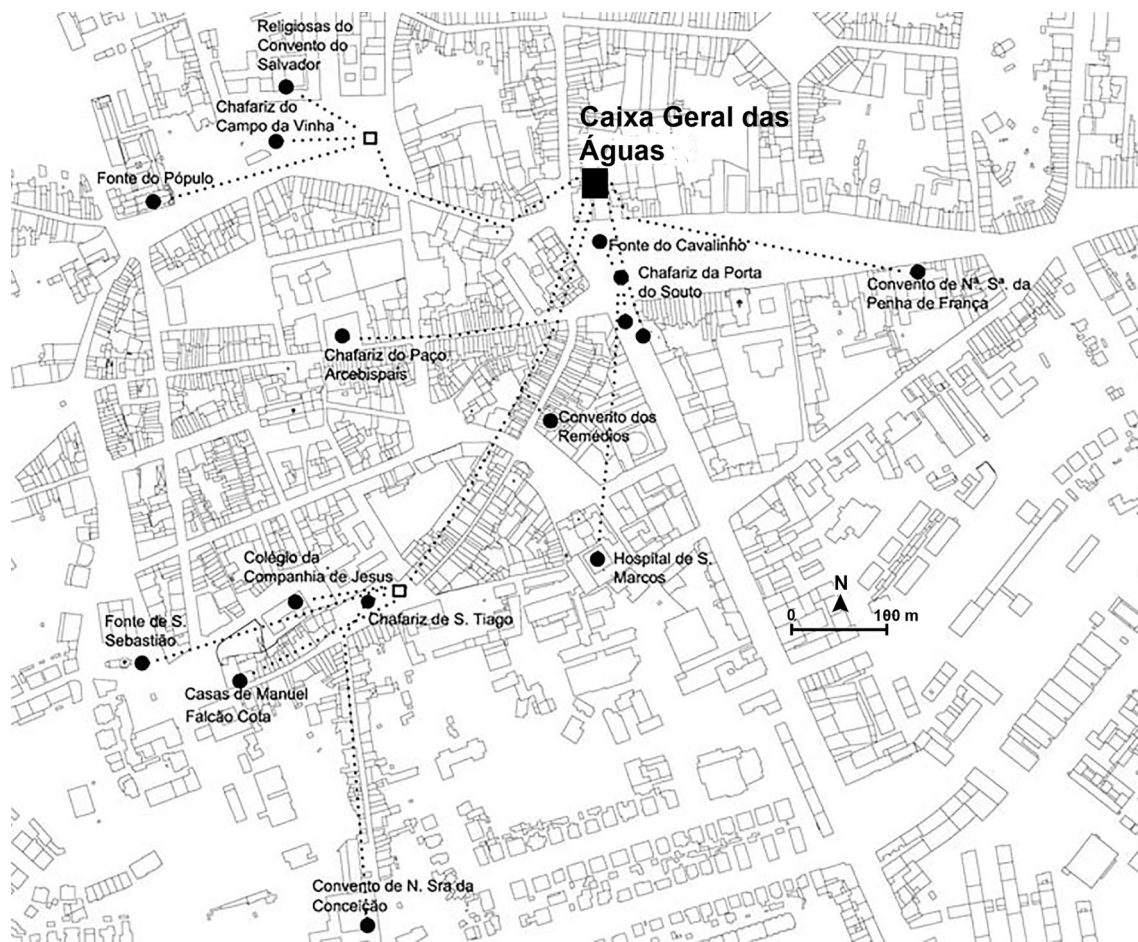


Fig. 6 Mapping of the water urban distribution, in the city of Braga, in mid-eighteenth century (adapted from Martins et al. 2011a)

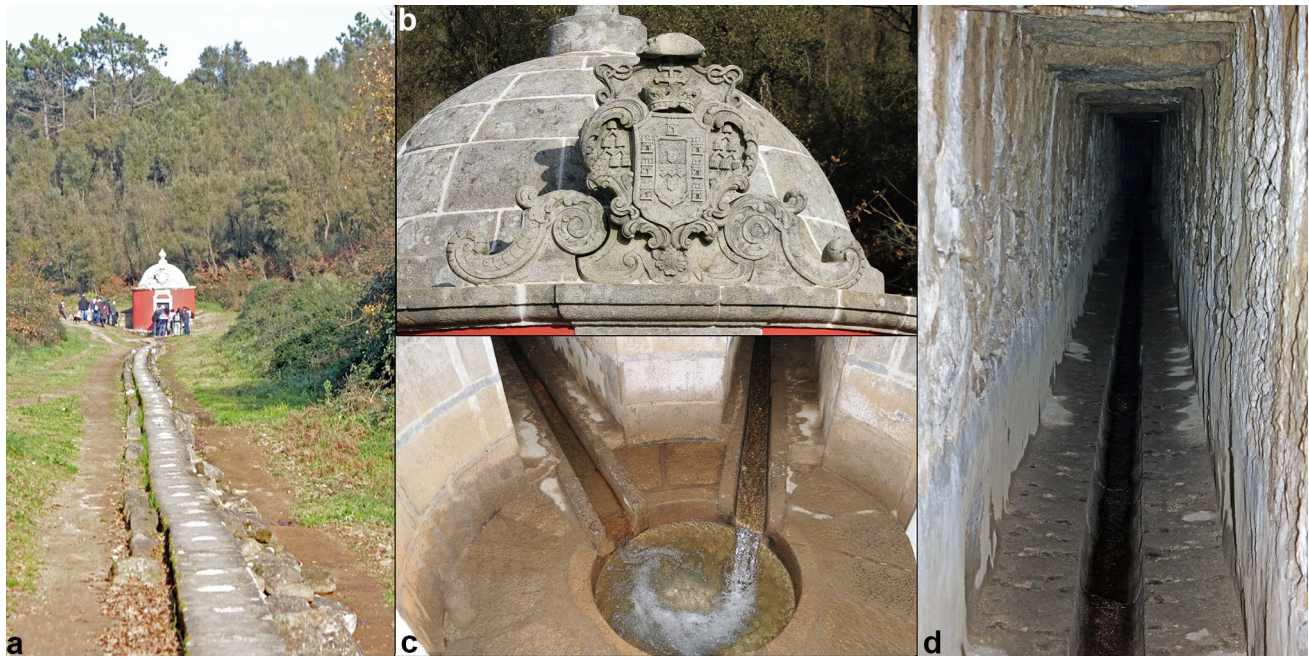
## Modern age

The beginning of the sixteenth century witnessed a new stage of urban development in Braga, associated with the archbishop D. Diogo de Sousa (1509–1534), who significantly improved the city's hydraulic system (Martins et al. 2012). The demographic and economic growth of the city in this period also brought the increasing need of searching for new local water sources (whether in the urban space or on its surrounding territory). The archbishop's actions were an answer to the rising needs of a growing city, that was demanding improved distribution and draining structures, as well as a new public fountains' network.

Several other archbishops, during the subsequent periods, intervened in the water supply system of Braga, enhancing its water distribution network with the construction of new public fountains, such as D. Frei Agostinho de Jesus (1588–1609). The number of fountains and waterworks established throughout the sixteenth century demanded a supply system from outside the city (Martins et al. 2012), and from the seventeenth century onwards

the written sources gave notice to the purchase of land and the construction of conducts located around the Sete Fontes, Passos, Areal and Montariol areas (Ribeiro and Martins 2012). D. Rodrigo de Moura Teles (1704–1728) implemented the diversification of the water collection, seepage tunnels and dipping tunnels places that were built and the water from Sete Fontes was channelled through an underground aqueduct towards the Caixa Geral das Águas located at one of the city's entrances (Martins and Ribeiro 2012). These works performed the base of what is today known as Sete Fontes hydraulic system.

This system was improved by the archbishop D. José de Bragança (1744–1752), who ordered the monumentalization of the water source complex by building new galleries and “chapels” (round chambers with arched roof) that boast of his coat of arms (Fig. 7), and by D. Caetano Brandão (1790–1805) who ordered the opening of a gallery around 1804 (Mina dos Órfãos de S. Caetano) to supply water to an orphanage founded by him (Orphans of S. Caetano) (Martins et al. 2012; Ribeiro and Martins 2012; Vieira et al. 2016).



**Fig. 7** Sete Fontes water source system (Braga, eighteenth century). **a** “Chapel” and the covered stone aqueduct. **b** D. José de Bragança coat of arms located on one of the “chapels”. **c** Detail of a “Chapel” interior, with the entrance of two galleries, and the water treatment

system used to perform: aeration; gas transfer; iron and manganese removal; sedimentation. **d** Underground mine gallery that connect the springs to the “chapels”

The Sete Fontes water supply system, built in the eighteenth century, abstracts the water from the Sete Fontes aquifer, being composed of: underground branched galleries (eleven of them are still active) collecting spring waters; (covered) stone aqueduct channels about 3500 m long for water transportation to the city; cisterns for water storage; waterspouts and fountains for public water distribution (Vieira et al. 2016).

Analyzing the orography and geology of nearby surroundings of Braga, one can easily explain the fact that the major water sources, in the eighteenth century (Monteariol, Sete Fontes and Gualtar), are located to the north and north-east, where the springs are abundant, and the hillsides have a very favourable declivity to its gravity transport into the city (Rodrigues 2012; Vieira et al. 2016). In fact, these water sources have altitudes ranging between 250 and 300 m, while the main reservoir (Caixa Geral das Águas), for water storage and distribution, should be at a topographic elevation of about 194 m. This situation allowed avoiding the need of upraised structures for water transport that might justify the curious lack of a monumental aqueduct in Braga (Ribeiro and Martins 2012).

### Contemporary age

The Sete Fontes was the main water system in the city of Braga until 1913, when a new abstraction and treatment

system was installed in the Cávado river, from where the southern area of the city was served by pumping water to the Guadalupe reservoirs (Vieira et al. 2016). However, most of the city fountains and waterspouts (and some few houses) are still now supplied from this ancient water source system, whose daily productivity was estimated to be 500 m<sup>3</sup>/day (estimation of 1934, according to Vieira et al. 2016). Recent hydrogeologic studies from Rodrigues (2012) and Costa (2012) measured an average daily productivity of about 400 m<sup>3</sup>/day, for a normal hydrological year. In the third decade of the twentieth century, some iron pipes were introduced in some of the segments of the Sete Fontes water supply network, cast to prevent aquifer losses and facilitate its maintenance, without destroying the ancient infrastructure, and ensuring the continuity of its operation.

Since the Sete Fontes water system preserves both the original memorial role and their operational functions, its classification as a national monument was deservedly declared on 25th March 2011 (Vieira et al. 2016). Being that this aquifer was used for drinking water abstraction, the official notification also classifies it as a registered protected area. For its cultural significance, preserving its authenticity and integrity, the Sete Fontes water supply system has an unquestionable historical value as a national heritage and constitutes a strategic safe water source legacy that must be protected.



## Materials and methods

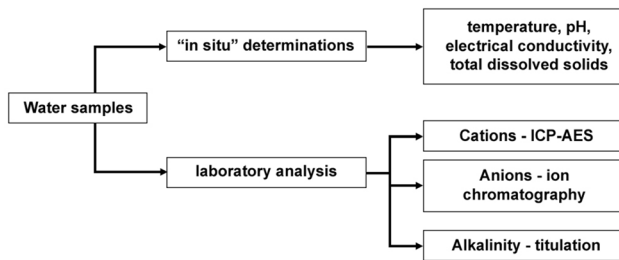
Groundwater geochemistry characterization and associated productivity were performed with selected groundwater samples (15 springs). The Sete Fontes system productivity was carried out over a period of 50 weeks, during the hydrological year of 2011–2012, with the flow rates determination using calibrated containers and a digital timer with a resolution up to hundreds of seconds. The inherent errors associated with the methodology were minimized through the control of some factors, such as the systematic use of the same equipment, the multiplicity of the flow measurements (four times at each spring) and the readings performed by the same operator. Water sample analyses included “in

situ” determinations and laboratory analysis of major cations and anions (Fig. 8), to evaluate the main regional hydrogeochemical facies. The groundwater samples were collected and analysed in 4 months (October 2011, January 2012, April 2012 and May 2012; Costa 2012) to obtain a seasonal groundwater geochemistry characterization.

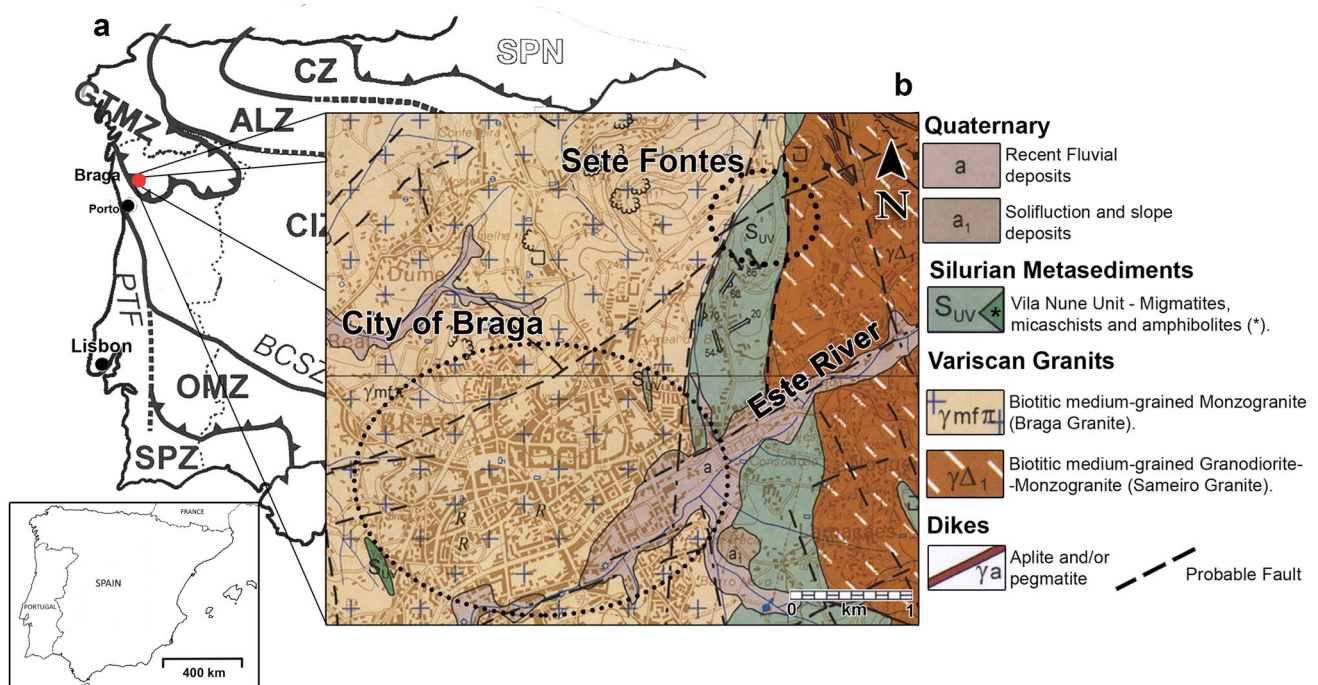
## Sete Fontes groundwater system

### Geology and hydrogeology background

The Sete Fontes groundwater system is located on the NE outskirts of the city of Braga (NW Portugal) at the following coordinates: latitude: N41°34′08.45″; longitude: W8°24′14.58″ (WGS 84 Web Mercator). The region is located in the Galiza Trás-os Montes (GTM) geotectonic zone of the Iberian Massif (Ribeiro et al. 2007; Dias and Ribeiro 2013), which occupies the western and central part of the Iberian Peninsula (Fig. 9a). The area is dominated by the contact of Variscan granitic rocks, distributed in allochthonous terrains. One of the most striking features of this zone and the Central Iberian Zone (CIZ) is the presence of granitoid rocks, related to Variscan magmatism, with different implantation ages: ante-, sin-, late- and post-D3 (Ferreira et al. 1987). In the region, most of the granitic rocks show a clear relation to the Vigo-Régua shear zone (Fig. 9a), assuming, therefore, a cartographic expression that follows,



**Fig. 8** Schematic representation of groundwater analysis methodology



**Fig. 9** **a** Geological setting of the study area in the Iberian Peninsula; **b** Geological map of Sete Fontes area (Braga, Portugal). Geological background adapted from Ferreira et al. (2000) and Ribeiro et al. (2007)



in general, the orientation of this megastructure and the late-Variscan tectonic movements (Lima 2001).

The Sete Fontes aquifer is characterized by the contact of Silurian metasediments (essentially biotite micaschists and migmatites), comprising the Vila Nune allochthonous unit, with Variscan biotite granites (Sameiro and Braga granites).

The contact between the granites and the Silurian unit occurs along faults, trending NNE–SSW and NNW–SSE. The main area of the catchment is crossed by a NE–SW tectonic lineament. The granites are, generally, fractured and weathered to different grades, from fresh rock to residual soil, showing highly variable conditions, resulting in arenisation, which may reach depths of more than 20 m. The metasediments are also fractured and weathered to different grades, from slightly weathered to moderately weathered. Micaschists and migmatites present associated quartz veins with a favourable hydrogeological characteristic, increasing its permeability and promoting water infiltration from the surface and its percolation to depth.

The Sete Fontes area, included in the Portuguese Minho region, is part of the most representative geomorphological unit of the Iberian Peninsula, the Central Plateau (Brum Ferreira 1980; Carvalho et al. 2005). The geomorphology of Braga region is strongly marked by the contrast between high reliefs and deep valleys, following preferential orientations

defined by a tectonic origin (Ferreira et al. 2000). The area presents two main fracturation trends—ENE–WSW and NW–SE—which partially controls the groundwater flow (Fig. 9b).

Geological fieldwork was carried out to identify major groundwater circulation paths and a hydrogeological field inventory is represented in Fig. 10. The groundwater system is composed of several underground galleries collecting spring waters, stone aqueduct channels with about 3500 m long for water transportation, cisterns for water storage, waterspouts and fountains for public water distribution (Vieira et al. 2016).

The water sources of the Sete Fontes water system are in a valley with a NE–SW trend and altitudes ranging between 250 and 300 m (Figs. 10, 11), with the main reservoir (water storage and distribution) in a topographic elevation of approximately 194 m. The water emergencies occur mainly along the valley, with drainage towards the south, and afterwards to the East river. This relief is especially important to the aquifer recharge, directly from precipitation or stream network. The geomorphology of the area causes a favourable slope to water–gravity transport into the city.

The county of Braga has an area of about 183.15 km<sup>2</sup> and its hydrography is dominated mainly by three water courses: Cávado river (on the north), Ave river (on the south) and

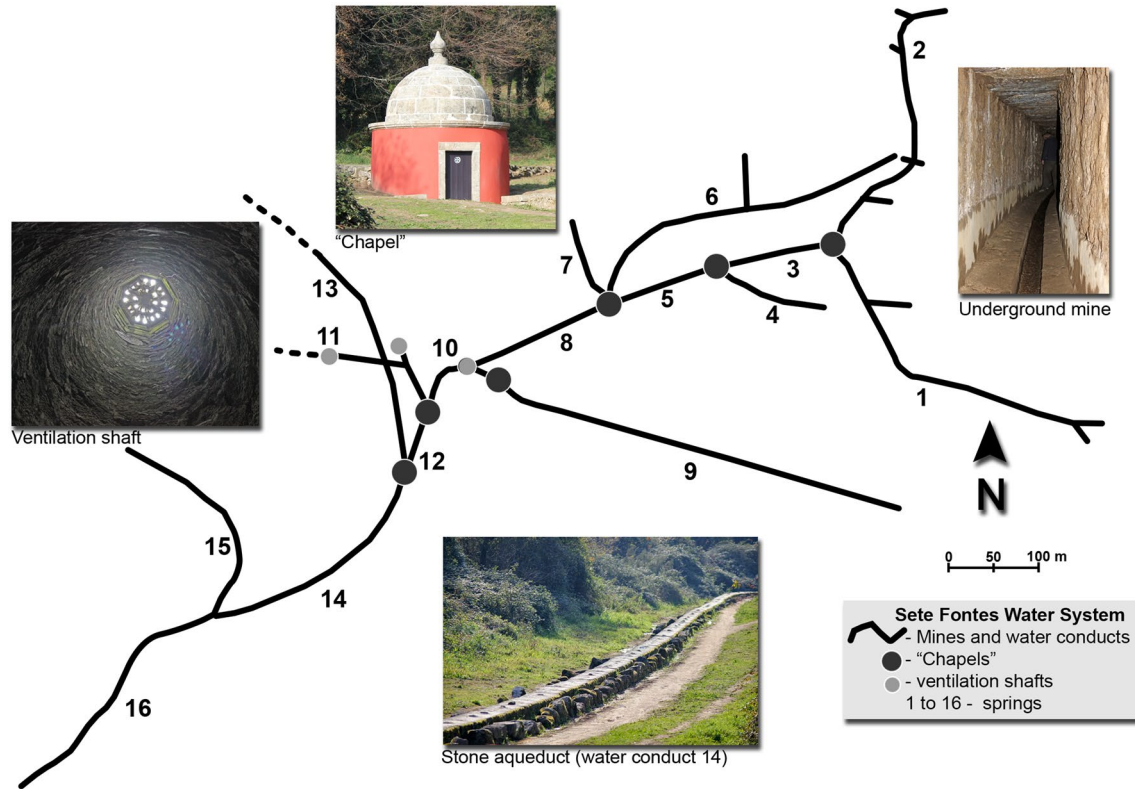
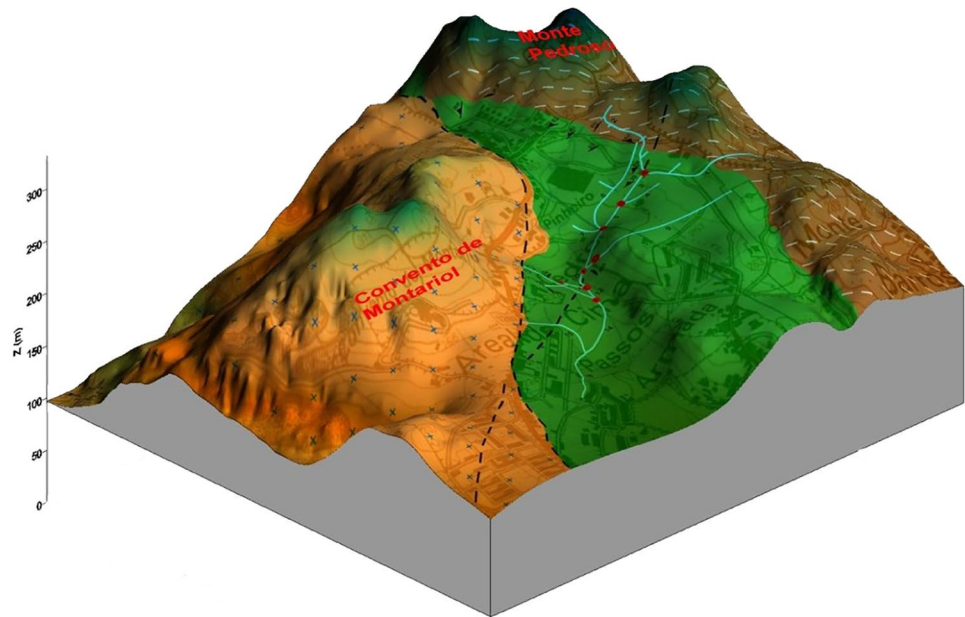


Fig. 10 Illustrative diagram of Sete Fontes groundwater system (adapted from Costa 2012)

**Fig. 11** Schematic three-dimensional representation of the relief of the study area (adapted from MB 2011)



Este river, whose courses are influenced by the dominant fracturation systems. In the last decades, the economic and demographic growth of Braga lead to the increasing need for exploration of other water resources. Nowadays, the city is supplied by water abstracted from Cávado River. However, most of city fountains and waterspouts are still supplied by the Sete Fontes water system, with an estimated daily productivity of 5.8 L/s (Vieira et al. 2016). The abundance of water resources in the area is due to the high rainfall that characterizes the region of Braga. The average rainfall is 1674 mm/year and the average temperature is 14.5 °C. The actual evapotranspiration was estimated to range between 618 and 640 mm (Costa 2012).

### Groundwater hydrogeochemistry

The variability of flow rate and groundwater physico-chemical composition of Sete Fontes during the hydrological year of 2011–2012 is summarized in Table 1. Water hydrogeochemistry results revealed a poorly mineralized water, with a maximum electrical conductivity of 195  $\mu\text{S}/\text{cm}$  and an average total mineralization of 85.1 mg/L, suggesting meteoric waters, with a relatively short deep and shallow circuit, and some water–rock interaction. The chemical composition of major dissolved salts in water is a mechanism mainly controlled by aquifer lithology or rock weathering, atmospheric precipitation and evaporation–crystallization processes (Prasanna et al. 2010; Marghade et al. 2012; Bozdogan and Gómez 2013; Afonso et al. 2017).

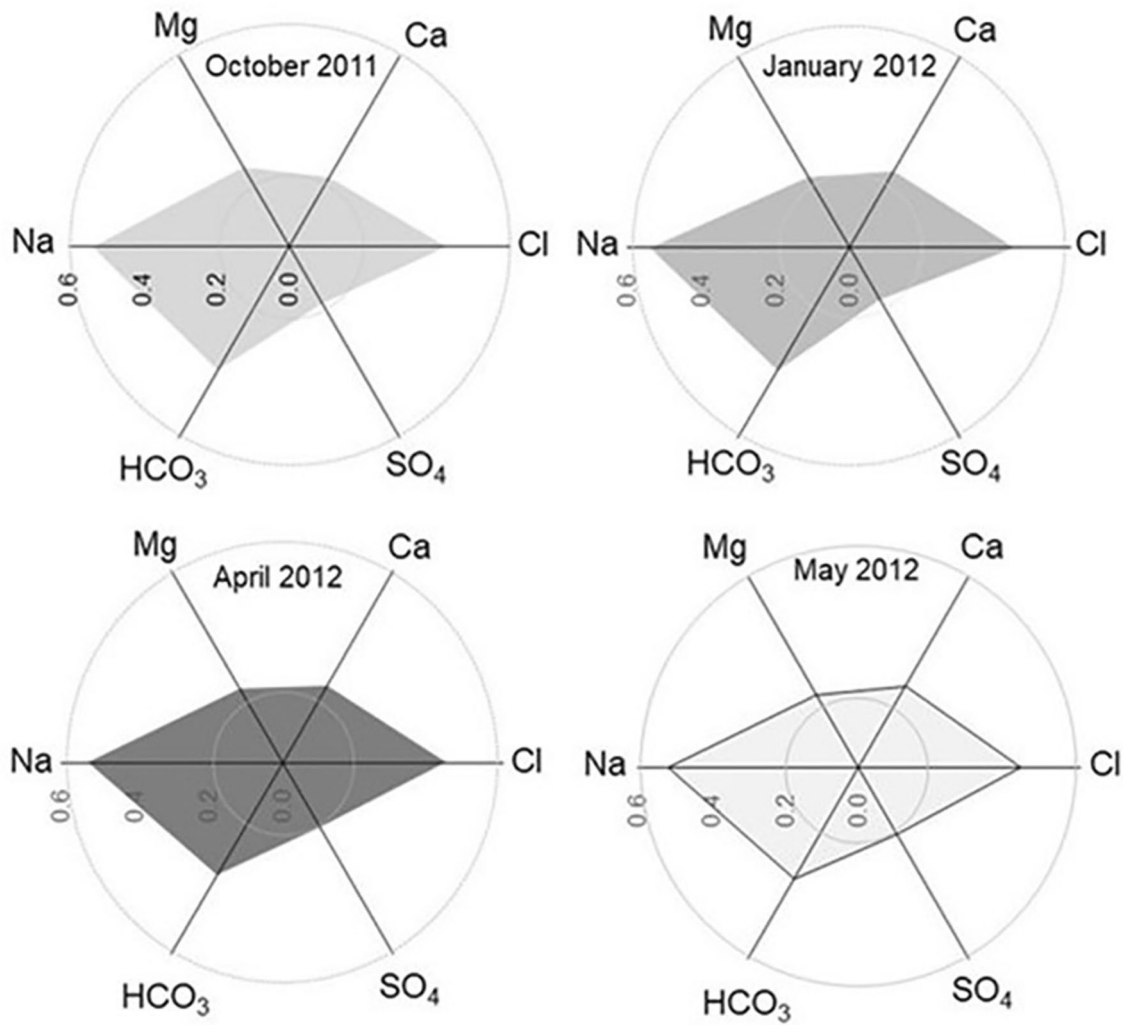
Groundwater has an average alkalinity of 12.9 mg/L  $\text{CaCO}_3$  and a neutral feature (pH 5.7–7.4) with more acidic values related to the granitic groundwater circulation. The

**Table 1** Flow rate (Q) and groundwater physico-chemical composition of Sete Fontes (adapted from Costa 2012)

	Minimum	Maximum	Average
Q ( $\text{m}^3/\text{dia}$ )	271.3	1183.4	547.2
T (°C)	13.4	16.2	98
EC ( $\mu\text{S}/\text{cm}$ )	45	195	98
pH	5.7	7.4	6.8
TDS (mg/L)	45.0	150.0	85.0
Alkalinity (mg/L $\text{CaCO}_3$ )	7.0	19.0	10.4
Na (mg/L)	5.8	19.5	10.4
K (mg/L)	0.4	3.0	1.8
Ca (mg/L)	1.1	26.0	3.7
Mg (mg/L)	0.6	4.9	2.8
Cl (mg/L)	4.7	15.7	8.1
$\text{NO}_3^-$ (mg/L)	0.0	40.3	9.8
$\text{SO}_4^{2-}$ (mg/L)	0.4	16.3	3.8
$\text{HCO}_3^-$ (mg/L)	0.9	8.0	2.5

hydrogeochemical facies of groundwater are mostly Na–Cl type, according to Piper classification. Locally, there is also a Na– $\text{HCO}_3$  facies type. The dominant cation trend was in the order of  $\text{Na} > \text{Ca} > \text{Mg} > \text{K}$ , except in October with  $\text{Na} > \text{Mg} > \text{Ca}$ , and the dominant anion trend was in the order of  $\text{NO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-$ . The radial diagram shows the ionic trends in groundwater of the Sete Fontes area due to infiltration and flow rate; with similar results in all the months. There is no significant seasonal variation between groundwater collected during the hydrological period (Fig. 12).





**Fig. 12** Radial diagrams showing major ion chemistry from Sete Fontes groundwater

Most of groundwater samples collected in the 4 months fall in the atmospheric precipitation dominance and only a few groundwaters show a rock weathering dominance, by plotting  $(\text{Na} + \text{K})/(\text{Na} + \text{K} + \text{Ca})$  versus TDS (Fig. 13a), suggesting a maritime influence and local human contribution. Relatively to the ratio  $\text{Cl}/(\text{Cl} + \text{HCO}_3)$ , groundwater mineralization is controlled by the rock weathering (Fig. 13b).

Water geochemistry from Sete Fontes is mainly controlled by water–rock interaction, associated with a maritime influence (e.g., Mg, Na and Cl) and a local agricultural and human contribution (e.g., NO<sub>3</sub>, SO<sub>4</sub>) (Costa 2012).

The individual yield of the different springs from Sete Fontes is highly variable, with a minimum flow rate of 0.1 m<sup>3</sup>/day and a maximum of 422.6 m<sup>3</sup>/day. The overall productivity of the system, in the hydrological year of 2011–2012, has a minimum rate flow of 271.3 m<sup>3</sup>/day (April/2012) and a maximum of 1183.4 m<sup>3</sup>/day (May/2012), with an average value of 547.2 m<sup>3</sup>/day. Since this was a dry

year (average rainfall = 1674 mm/year and  $T = 14.5^\circ\text{C}$ ), it is expected that the average and maximum yield of the system may be greatly exceeded in an average year and, even more prominently, in a wet one. The springs are characterized by recession constant values ranging from  $10^{-2}$ /day to  $10^{-3}$ /day. The relationship between the spring's yields and their physicochemical parameters (Table 1) are well-reflected in the recharge events. Furthermore, there is a dependency between the water temperatures of some springs and the atmospheric temperature, suggesting shallow groundwater pathways.

## Conclusions

Groundwater water system from Sete Fontes preserves both the original memorial role and its operational function, so its preservation and valorization is a key urban asset of the city of Braga. The classification as a national monument was

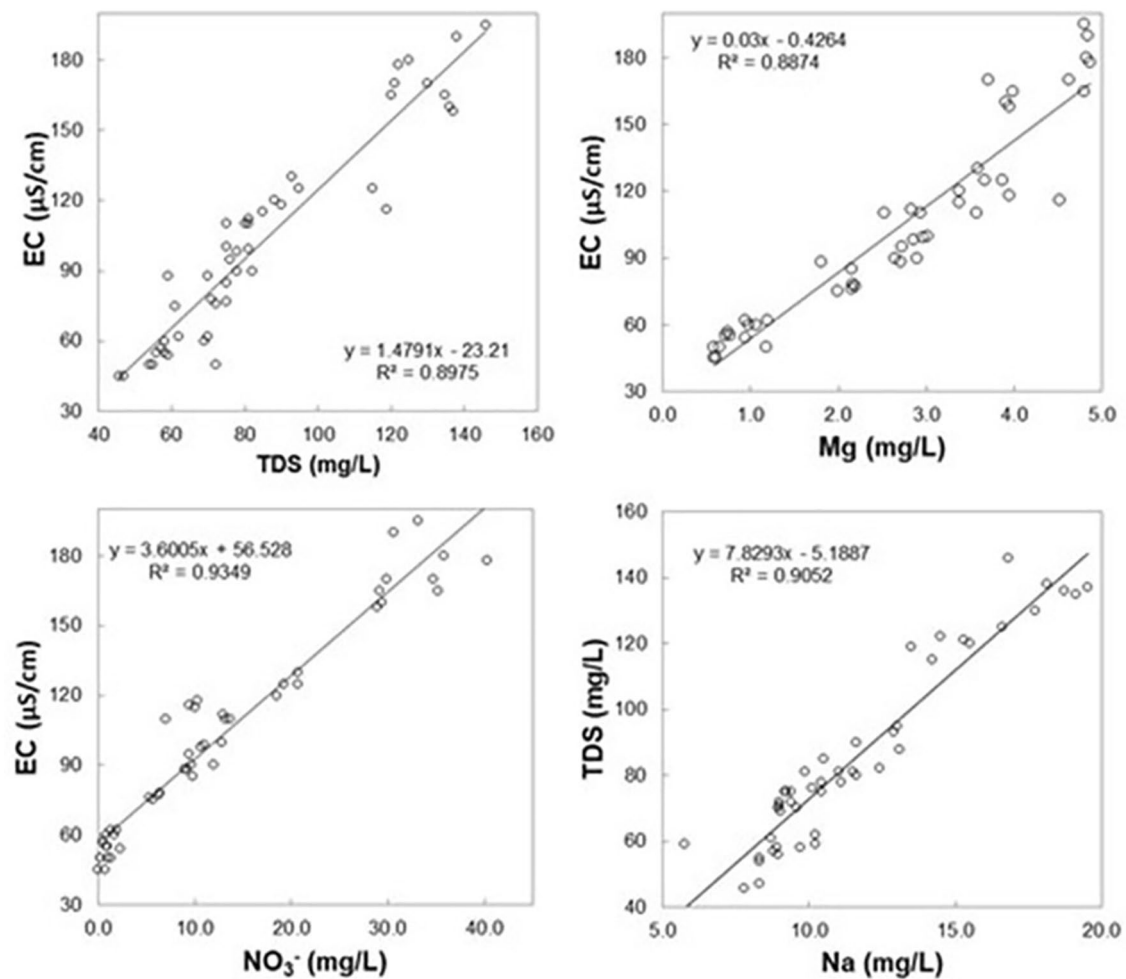


Fig. 13 Selected correlation diagrams between groundwater parameters from Sete Fontes

declared on the 25th March 2011. According to its cultural significance, bearing on its authenticity and integrity, the Sete Fontes water system receives an important historical value as a national heritage. The historical importance of the Sete Fontes aquifer is also enlarged if considered that during the Roman period this area was probably the main source of water for the city.

In the last decades, the economic and demographic growth of Braga lead to the increasing need of exploration of other water resources. Nowadays, the city is supplied by water abstracted from Cávado River. However, most of city fountains and waterspouts are still supplied by the Sete Fontes water system, without significant water quality problems. This study suggests that, from a hydrogeochemical perspective, Sete Fontes groundwater is suitable for human consumption and also for other urban uses (such as irrigation of parks and lawns, street cleaning and firefighting), and so it can be considered as a sustainable water resource for Braga municipality.

Groundwater resource characterisation in urban areas seeks to address several important information related to the sustainable management of local water resources. This usually provides specific and adequate methodologies to assess the interaction between surface and groundwater, attending the prevention and mitigation of possible contamination. A vulnerability assessment model of Sete Fontes groundwater system will be a future powerful tool for water resources management.

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