From historical hydrogeological inventory through GIS mapping to problem solving in urban groundwater systems

Helder I. Chaminé, Maria José Afonso and Liliana Freitas*

Water resources have had a huge impact on the socioeconomic sustainability and development of urban areas. The close relationship between water and human society has been important throughout the history of civilization. The water supply for early urban settlements included mainly the use of river canals, rainwater-harvesting systems, wells, aqueducts and underground cisterns. The industrialisation period in Europe promoted an increase in population and expansion of urban areas. Furthermore, several epidemics devastated European urban areas in the period between the18th and 19th centuries. Unhygienic conditions caused by polluted water, human and animal waste and excreta were among the main causes. This study discusses the importance of historical hydrogeological inventories in a large urban area, such as Porto city (NW Portugal), to better comprehend the evolution of urban water supply systems. In that approach urban geosciences need to advance towards a smart urban geoscience concept.

Les ressources en eau ont toujours été fondamentales pour la durabilité et le développement socio-économique des zones urbaines. La relation eau et société humaine a joué un rôle important tout au long de l'histoire des civilisations. L'approvisionnement en eau des agglomérations urbaines primitives comprend l'utilisation de canaux fluviaux, des systèmes d'eau de pluie-récolte, puits, aqueducs et citernes souterraines. La période d'industrialisation en Europe a favorisé une augmentation de la population et l'expansion des zones urbaines. En outre, plusieurs épidémies ont dévasté les zones urbaines européennes entre les 18e et 19e siècles. Mauvaises conditions d'hygiène dues à la pollution de l'eau, aux déchets humains et animaux et autres excréments en sont quelques-unes des principales causes. Cette étude analyse l'importance des inventaires hydrogéologiques historiques dans une grande région urbaine, telle que la ville de Porto (NO du Portugal), afin de mieux comprendre l'évolution des systèmes d'approvisionnement d'eau en milieu urbain. Dans cette approche les géosciences urbaines ont besoin d'évoluer vers le concept de géosciences urbaines soutenues par une technologie intelligente.

Los recursos hídricos han tenido un enorme impacto en la sostenibilidad socioeconómica y en el desarrollo de las zonas urbanas. La estrecha relación entre el agua y la sociedad humana ha jugado un papel importante a lo largo de la historia de las civilizaciones. El suministro de agua para los primeros asentamientos urbanos incluyó principalmente el uso de cursos fluviales, sistemas de siembra de agua de lluvia-cosecha, pozos, acueductos y cisternas subterráneas. El período de la industrialización en Europa promovió un aumento de la población y la expansión de las áreas urbanas. Por otra parte, varias epidemias devastaron zonas urbanas europeas entre los siglos 18 y 19. Entre las principales causas estuvo la contaminación, y los residuos y excrementos humanos y de animales. Este estudio analiza la importancia de los inventarios hidrogeológicos históricos en una gran área urbana, como la ciudad de Porto (NO de Portugal), para comprender mejor la evolución de los sistemas de abastecimiento de agua en medios urbanos. En ese enfoque las geociencias en medio urbano necesitan avanzar hacia el concepto de geociencias en medio urbano apoyadas con tecnología inteligente.

Urban geoscience, water, and mapping: towards a smart urban geoscience concept

Urban areas, independently of the socioeconomic development and administrative importance of their parishes, villages, towns or cities, play a key role in the lives of most populations. Nowadays cities face challenges like being innovative, competitive, creative, sustainable, inclusive and resilient. The newest goal for urban areas is to be smart. So, the cities of tomorrow are presently a reality (EU, 2011). That pioneering approach includes the integration of numerous data about all features of the urban areas – transport, environment, economy, housing, culture, science, population, health, history, architecture, heritage, etc. – through a series of interactive graphs, maps and digital technology. In that perspective urban geoscience needs to evolve to a new paradigm of a smart urban geoscience, particularly related to geology, hydrology, groundwater, rock and soil geotechnics, natural resources, environment, geohazards, geoheritage and geoarchaeology issues (***Fig. 1***). A core aspect for the smart urban geoscience concept necessarily includes Geographic Information Systems (GIS) as a tool for digital mapping (e.g., Chaminé *et al.*, 2010; Petitta, 2013; Freitas *et al.*, 2014).

* Laboratory of Cartography and Applied Geology (LABCARGA), Department of Geotechnical Engineering, School of Engineering (ISEP), Polytechnic of Porto, Portugal, hic@isep.ipp.pt

Since water is an essential part of the environment, the hydrology of urban areas should be seen as a vital key in all successful urban planning and management tasks and in the sustainability of ecosystems. A Chinese saying states this vital issue: *"when you drink the water, remember the spring"*. This inspirational quotation is the basis for the key role of water resources for drinking purposes. Throughout the ages, supplying water from rivers, lakes, wells or springs has been a regular task for mankind. The supply network for fresh water emerged alongside the construction of cities, towns or villages.

There are reports of water supply to the urban settlements from the Bronze Age

Figure 1: Cloud diagram based on keywords about the smart urban geoscience concept.

(2800–1100 BCE), that comprise the use of river canals, rainwater-harvesting systems, wells, aqueducts and underground cisterns (e.g., Wittfogel, 1956; Bono and Boni, 1996; Angelakis *et al.*, 2012, Freitas *et al.*, 2014). In the past, public fountains were a social meeting place, while people collected water for drinking or bathing (Chaminé *et al.*, 2010). The Romans established an organised system of aqueducts, fountains, siphons, cisterns and sewers, channelling water to create public bath sites and temples dedicated to gods of healing (e.g., Wittfogel, 1956; Bono and Boni, 1996; Angelakis *et al.*, 2012; and references therein). In the Middle Ages, water was distributed often by private water carriers. With the empirical methods of the 19th century, modern societies began addressing issues of water supply more carefully. By the mid-20th century water usage issues like availability, management and competition were becoming increasingly relevant due to pressing environmental and resource concerns (Angelakis *et al.*, 2012). One method for understanding the complexity of Earth systems (lithosphere, hydrosphere, and atmosphere) is the use of ground models, in which the basic approach is the observation, description, analysis, assessment and modelling of the natural systems. Thus, urban geology or more broadly the so-called urban geoscience, is an interdisciplinary field encompassing geology, engineering geosciences, environmental sciences and socioeconomic sciences addressing Earth-related problems in urbanised areas (McCall *et al.*, 1996). That overall framework is related to the impact of humans as geologic agents, predominantly in urbanised regions.

Man-made excavations on rock masses are often reported in old settlements, villages, towns or cities. These constructions sometimes consisted of an intricate network of tunnels or galleries, which were excavated to facilitate transportation, drainage, sewerage and a water supply system for the population (e.g., Gray, 1940; Wittfogel, 1956; Bono and Boni, 1996; Afonso *et al.*, 2010; Chaminé *et al.*, 2010; and references therein). Therefore, the underground in urban areas today frequently contains a complex system of dug spaces and buried

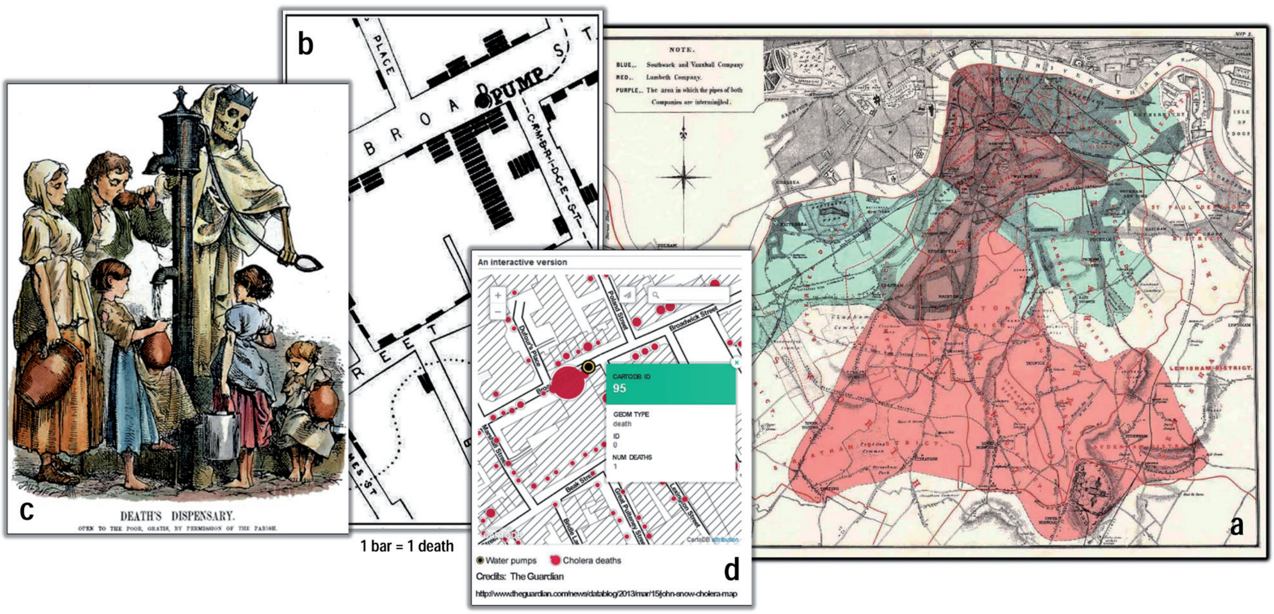


Figure 2: Snow's maps of cholera outbreak in the London region; a) the map describes the so-called grand experiment of 1854 comparing cholera mortality among persons consuming polluted water (Southwark and Vauxhall Company: blue-green on the map) versus cleaner water (Lambeth Company: red). The overlapping area (grey-reddish on the map) represent where the pipes of both companies are intermingled (Snow, 1855); b) an extract of Snow's map showing a pump exactly at the corner of Cambridge Street and Broad Street (adapted from Snow, 1855 and Brody et al., 2000); c) a drawing of the contaminated water pumps by George J. Pinwell, entitled "Death's Dispensary", published in the Victorian magazine "Fun" during the cholera epidemic of 1866; d) presently the use of interactive maps published in "The Guardian Data Blog" section: cholera deaths and pump information from John Snow's 1854 map of the cholera outbreak in London (adapted from "The Guardian", ***http://www.theguardian.com/news/datablog/2013/mar/15/****).*

structures, where anthropogenic materials are used to cover, hide or change the natural environment (Freitas *et al.*, 2014). However, these underground conduits regularly have obstructions and leakages which affect the urban water cycle (e.g., Afonso *et al.*, 2010; Chaminé *et al.*, 2010). In addition, the knowledge of aquifer characteristics in large urban areas is still scarce and there are several issues to assess, like uncontrolled exploitation and/or indiscriminate sewage and bad waste disposal practices which contribute to groundwater resources degradation.

In this study, the importance of historical groundwater inquiries and/or inventories in ancient urban areas is discussed to better understand the evolution of water supply systems. Presently, the use of GIS-based mapping on urban hydrogeology is essential for the assessment of water resources. In addition, the cross-checking of reliable hydrohistorical studies with current hydrogeological investigations contributes decisively to the resolution of problems in urban groundwater systems and to the comprehension of the urban water cycle. Last but not least, the use of a multidisciplinary and transdisciplinary approach (e.g., historical documentation, archaeological hydraulic structures, subterranean geology, groundwater ecotoxicology, geomicrobiology, and urban groundwater studies) leads to an accurate assessment and protection of aquifers in urban areas, as well as contributes definitively to a reliable understanding of the impact of climate variability on water resources.

Water supply, sanitation and urban areas: hydrohistorical issues

Presently, over one half of the global population lives in urban areas (particularly, cities and towns), and this proportion is likely to grow rapidly. Moreover, nearly 70% of the European population lives in urban areas (EU, 2011). Urban areas are shaped by complex systems that use inputs such as water, energy, materials and nutrients. Groundwater is of particular concern, as it represents over 95% of the world's freshwater reserves, and supplies over 1.5 billion city inhabitants for drinking and sanitation purposes (Howard, 2014). So, abstracting freshwater from a surface or groundwater source will not be possible in the near future, since it will affect the sustainability of the resource. Urban development requires new approaches that reduce water resource consumption and focus on resource recovery. According to Howard (2014) the fundamental principles of sustainable groundwater management in urban areas are very recent and, in some cases, still growing. Consequently, all involved agents (municipalities, decision makers, stakeholders, scientists, practitioners and individuals) are still learning about those values. Petitta (2013) argues that a blueprint vision should be highlighted and developed with the collaboration of hydrogeologists.

Interest in the relationship between urban epidemics and water dates back to the early 1800s, particularly during many severe pandemics (cholera and typhoid fever) spanning 1826 to 1866 (e.g., Lardner, 1833, 1855; Snow, 1855; Gray, 1940; Jackson, 2013; Freitas *et al.*, 2014; and references therein). Cholera and typhoid fever are bacterial diseases that are acquired by the consumption of water and food that has been contaminated by sewage. It was in the middle of the 19th century that the waterborne nature of cholera was first argued by the anaesthesiologist John Snow (Snow, 1855), contrary to prevailing theory that diseases were spread by miasma in the air.

The created cholera maps and the urban inquiry survey were important tools to confirm Snow's theory (***Fig. 2***). Afterward, two others key studies were published: Flint (1873) confirmed the typhoid fever was related to drinking polluted groundwater and Orton (1874) noticed the close relationship between geology and contaminated groundwater could lead to human diseases. Epidemics and pandemics are spatial phenomena (Koch, 2011). Mapping them is a great challenge and embedding in the map several basic and specific types of information (e.g., congested housing, fetid local waste site, marshy swamp, dug wells, and springs) was a great improvement (Koch, 2011; Jackson, 2013).

Brody *et al.* (2000) argue that Snow's map of the epidemic area was simply the visual representation of a deduction from a theory of transmission developed earlier, which in turn was grounded in a theory of the pathology of cholera as primarily a disorder of the gastrointestinal tract. However, the scientific legacy of Snow's

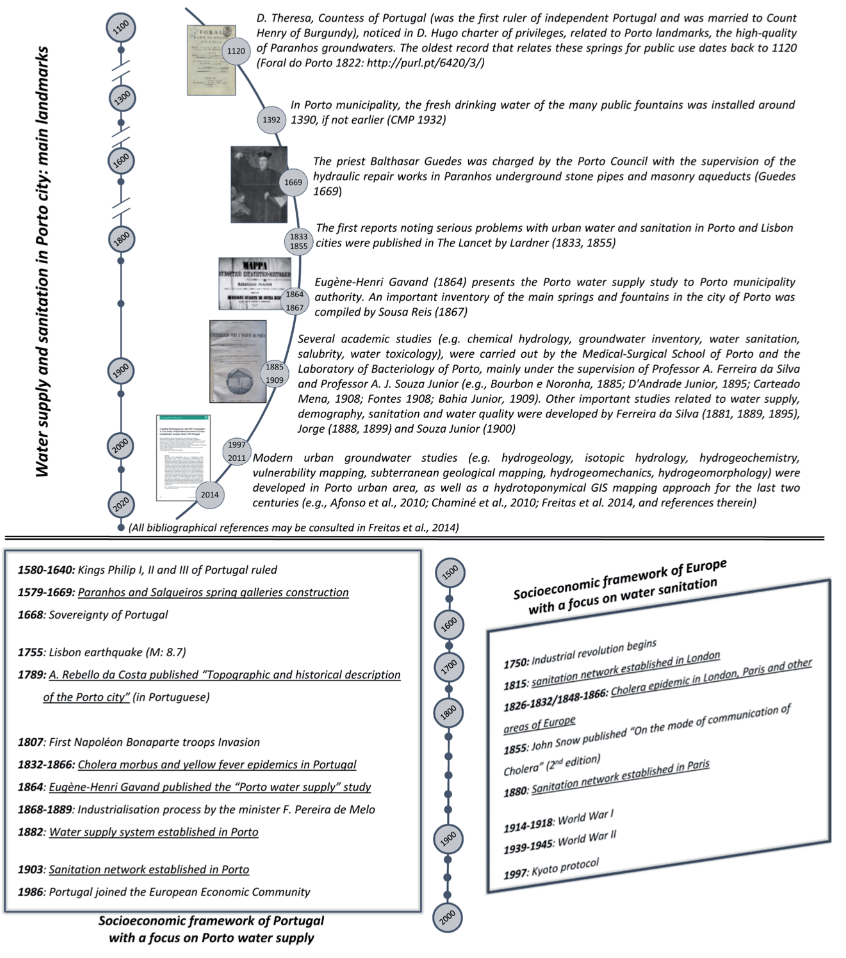
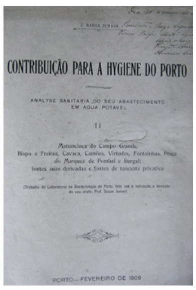


Figure 3: Outline of historical landmarks related to the water supply and sanitation in Porto urban area, as well as a comparative socioeconomic framework and landmarks in water sanitation in Portugal and Europe (revised and updated from Freitas et al.*, 2014).*

Table 1: *Groundwater and water toxicology key studies in Porto urban area developed by the Medical-Surgical School of Porto and the Laboratories of Bacteriology and Hygiene of Porto, in the early 20th century, under the guidance of Professor A. J. de Souza Junior.*

Date	*Groundwater key studies in Porto urban area (in portuguese)*	*Original cover*	*Publisher*	*Type of documentation Historical repository source*	*Biographical note*
1908, May	***Adriano Fontes:** Contribuição para a hygiene do Porto: analyse sanitária do seu abastecimento em agua potável. I: estudo dos mananciaes de Paranhos e Salgueiros / **Contribution to the study of Porto city hygiene: sanitary analysis for the potable water supply. I. Study of Paranhos and Salgueiros springs.** 172 p.*	 	*Escola Médico-Cirúrgica do Porto, Laboratório de Bacteriologia do Porto Medical-Surgical School of Porto, Laboratory of Bacteriology of Porto Typographia Encyclopedia Portugueza, Porto*	*Dissertação Inaugural **Graduation Dissertation** **http://hdl.handle.net/10216/17066***	***Adriano de Figueiredo Fontes** earned the Bachelor of Medicine in 1908; served as a military physician (Lieutenant) in the Portuguese army; was appointed 2nd provisional trainee teacher (8th course) in 1912 in the Faculty of Medicine, University of Porto (DR Nº89-16.Fevereiro.1912, p.646). He also practiced medicine during his career.*
1908, July-November	***José Carteado Mena:** Contribuição para o estudo da hygiene do Porto: analyse sanitaria do seu abastecimento em água potável. III: estudo sobre os poços do Porto / **Contribution to the study of Porto city hygiene: sanitary analysis for the potable water supply. III. Study about Porto dug-wells.** 270 p.*	 	*Laboratórios de Bacteriologia e Hygiene do Porto **Laboratories of Bacteriology and Hygiene of Porto** Typographia Encyclopedia Portugueza, Porto*	*Relatório Técnico-Científico **Technical-Scientific Report***	***José Casimiro Carteado Mena** (1876-1949) obtained the Bachelor of Medicine in 1902; served as a military physician in the Portuguese army, reaching the rank of Major; was appointed Head of Institute Pasteur, in Porto. He developed pioneering radiological studies in medical applications.*
1909, February	***José Bahia Junior:** Contribuição para a hygiene do Porto: analyse sanitaria do seu abastecimento em agua potavel. II: Mananciaes do Campo Grande, Bispo e Freiras, Cavaca, Camões, Virtudes, Fontainhas, Praça do Marquez de Pombal e Burgal; fontes suas derivadas e fontes de nascente privativa / **Contribution to the study of Porto city hygiene: sanitary analysis for the potable water supply. II. Study of the Campo Grande, Bispo e Freiras, Cavaca, Camões, Virtudes, Fontainhas, Praça do Marquez de Pombal and Burgal springs; related fountains and private springs.** 111 p.*	 	*Escola Médico-Cirúrgica do Porto, Laboratório de Bacteriologia do Porto **Medical-Surgical School of Porto, Laboratory of Bacteriology of Porto** Typographia Encyclopedia Portugueza, Porto*	*Dissertação Inaugural **Graduation Dissertation** **http://hdl.handle.net/10216/17030***	***José da Silva Ferreira Bahia Junior** (1882-1968) received the Bachelor of Medicine in 1909. He practiced psychiatry during his career and he was the director of the "Conde Ferreira" psychiatric hospital in Porto.*

approach was indeed the use of rigorous deductive method and field inquiry surveys. Moreover, he proposed that spatial data and topographic terms were the basis to relate cholera outbreaks to the source of water and at the end of his approach he created useful illustrative maps (see Snow, 1855). Sanitary research in the 18th and 19th centuries was related to medical hydrology and engineering, which played a key role to the development of urban disease maps and the protection of water supply systems (see details in Koch, 2011).

Selected site: example from Porto urban area, NW Portugal

In 1833, the British physician William Lardner, the appointed director of the Foz Hospital, reported in the journal *The Lancet* several concerns about the malignant cholera in Porto city. In his own words: *"(...) The next evidence of the disease spreading, was the fact of several of the Portuguese and French soldiers, and the poor inhabitants of the village of Foz [do Douro], being at attacked; and, finally, it insinuated itself. Into the heart of the city, where it certainly committed less mischief than might have been anticipated; for poverty, foul air, and filth, universally prevailed."* (Lardner, 1833: 301). This impressive quotation illustrates the violence of the cholera outbreak and the unsanitary conditions in Porto urban area in the early 19th century. Lardner (1855) noted new cholera epidemic outbreaks in Lisbon and Porto cities. Several studies about the epidemics on the ground (like cholera, yellow and typhoid fevers) were reported throughout the 19th century by eminent Portuguese academics such as A. Bernardino Gomes, A. J. Ferreira da Silva, R. Jorge and A. J. de Souza Junior (details in Pires de Almeida, 2012; Freitas *et al.*, 2014).

Porto city is the second largest urban area in Portugal and has been developed in a discontinuous way, mainly related to the processes of city building and urban morphology dynamics. The city was settled on the granitic hill slopes close to the Douro river mouth (Carríngton da Costa, 1938). Porto city has been an important conurbation since the 12th century, being one of the oldest cities in Europe, and its old neighbourhoods in the historical centre were recognised by UNESCO as a World Heritage Site in 1996. Earlier settlements date back at least to the 5th century BC, in the days of Visigoths and Suevians, followed by Romans in the 1st century BC, who established an administrative and trading centre. The so-called Portus Cale (later Portucale and, in its non-Latin form, Portugal) was the previous designation for the Porto and Gaia settlements. Although this region changed hands more than once during the Moorish occupation in the Iberian Peninsula, the invaders were evicted definitively in AD 868, after which it remained Christian (Afonso *et al.*, 2010; Chaminé *et al.*, 2010; Freitas *et al.*, 2014; and references therein).

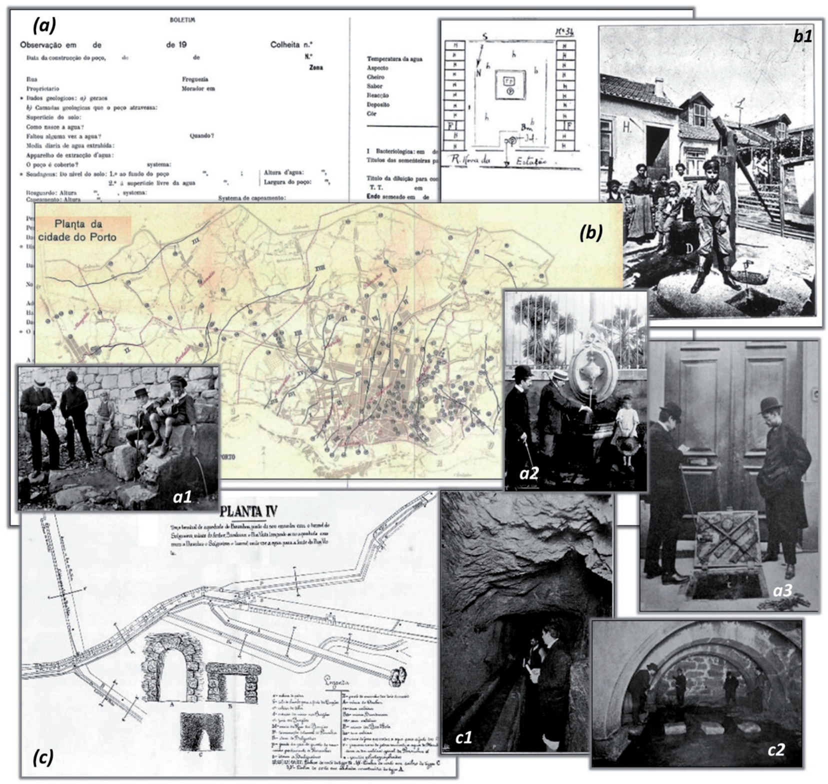


Figure 4: Several aspects of the urban fieldwork and mapping published in the Porto groundwater and water toxicology key-studies developed by A. Fontes (1908), J. Carteado Mena (1908) and J. Bahia Junior (1909), under the supervision of Professor A. J. de Souza Junior (see Table 1). (a) an excerpt of an original field hydrological inquiry bulletin created by J. Carteado Mena, 1908 [a1, a2: springs and fountains surveys – J. Bahia Junior, 1909; a3: sewage survey – A. Fontes, 1908]; (b) Porto dug wells map by J. Carteado Mena, 1908 [b1: dug-well survey and sketch framework of the surveyed well – J. Carteado Mena, 1908]; (c) underground water gallery map (Salgueiros spring) by A. Fontes, 1908 [c1, c2: water gallery with stone aqueduct and Arca d'Água masonry reservoir – A. Fontes, 1908].

Over more than six centuries, groundwater was supplied to the Porto urban area, mainly through springs and fountains, and fresh water was conducted through lead, ceramic or stone pipes by an intricate network of underground aqueducts (Afonso *et al.*, 2010). The use of these natural springs dates back to AD 1120. The main water galleries (Paranhos and Salgueiros springs), with a length of 3.289 km and a maximum depth of 21 m b.g.l., were dug out of a heterogeneous granitic rock mass under the densely populated urban area of Porto (Carríngton da Costa, 1938; Chaminé *et al.*, 2010). Nowadays, these underground galleries are a good example of geoarchaeological and geoheritage sites to preserve.

Porto municipality, the Laboratory of Chemistry of the municipality of Porto, Laboratories of Bacteriology and Hygiene of Porto, and the Polytechnic Academy of Porto have supported numerous pioneering studies highlighting groundwater inventorying, water supply, water toxicology, sewage and sanitation issues in the period between 1830 and 1930 (e.g., J.E.G. Leite, H.D. Souza Reis, E.-H. Gavand, A.J. Ferreira da Silva, R. Jorge, T. Bourbon e Noronha, A. D'Andrade Junior, C. Coelho, A. Antas, C.B. Champalimaud, A. Fontes, J. Carteado Mena, J. Bahia Junior, A. Sá, A.G. Lemos, A.M. Guedes; see references to these studies in Freitas *et al.*, 2014). Porto city achieved high standards of water supply and sanitation in the early 20th century. ***Figure 3*** outlines the evolution of the foremost historical issues concerning the water supply and sanitation in the Porto urban area, as well as the overall framework in Portugal and Western Europe.

Porto's urban groundwater systems were seriously degraded, both in quantity and quality, by very poor sanitation infrastructures and hygiene practices beginning in the early 19th century. In addition, urban sewage arrangements were poor and often fetid water was fed into the water supply system. ***Table 1*** shows at a glance an outstanding set of key studies developed during the years 1908-1909 related to sanitary investigations for the potable water supply. These scientific studies were designed by A. J. de Souza Junior, head of the Laboratory of Bacteriology of Porto and a distinguished professor of medicine of the Polytechnic Academy of Porto. In this overall framework the urban fieldwork, the water inquiry bulletins and the hydrological mapping (surface and/or shallow underground water tunnels surveys) played a key role in the development of reliable groundwater and water toxicology studies (***Fig. 4***).

The reports were unusual because each constituted a unique set under the main theme *"Contribution to the study of Porto city hygiene: sanitary analysis for the potable water supply"* (***Table 1***), with three interrelated parts making up a comprehensive description about topographic, geologic and hydrological conditions, hydro-sanitary and water toxicology analysis and hydrological mapping (I – underground water tunnels of Paranhos and Salgueiros springs; II – other springs and fountains; III – dug wells) of more than 550 pages, 445 images, 75 tables, 179 sketch maps and 10 survey maps. The set of volumes is outstanding regarding the design of the scientific approach, i.e., understanding problems in the field encompassing urban topography (surface and underground surveys), geology and hydrogeology, with careful data collection and field description, followed by exhaustive hydro-sanitary and water toxicology laboratorial analyses, as well as desk studies generating a set of valuable hydrological maps and a proposal for several sanitary and engineering actions. It still remains a remarkable achievement in the present day because of the high standards applied and is an amazing source for scientific, historical, archaeological and geoheritage studies (e.g., Afonso *et al.*, 2010; Chaminé *et al.*, 2010; Pires de Almeida, 2012; Freitas *et al.*, 2014; and references therein).

Recently several groundwater and hydrohistorical inventories have been performed in Porto's urban area, supported by field and desk techniques for urban hydrogeology and GIS-based mapping (e.g., Afonso *et al.*, 2010; Chaminé *et al.*, 2010; Freitas *et al.*, 2014; and references therein). These studies were supported by a comprehensive cross-check and analysis of historical sources and old mapping related to groundwater use (see ***Table 1***). In addition, more than 410 water sites were inventoried and over 100 sites are currently being monitored for field hydrogeology, hydrogeochemistry, groundwater ecotoxicology, geomicrobiology, engineering geosciences, subterranean geology, and radiological studies regarding a smart urban geoscience approach (***Fig. 5***).

Concluding remarks

Mapping has extensive applications, such as military operations, water resources, geosciences, engineering, environment, urban planning and heritage. This study points out the importance of coupling an historical groundwater inventory and GIS-based mapping to better understand the evolution of urban water supply systems. New challenges are emerging related to the assessment, abstracting and modelling of the urban water cycle. In this approach, urban geoscience studies assume greater importance in contributing to the concept of smart cities, particularly in urban areas with an extensive history and geoheritage.

Thus, innovative approaches are needed in the collection, analysis and integration of urban data, like groundwater ecotoxicology, geomicrobiology, urban speleology, subterranean geology, hydrogeomorphology and historical hydrotoponymy (e.g., Afonso *et al.*, 2010; Chaminé *et al.*, 2010; Freitas *et al.*, 2014). This study highlights the importance of the use of ancient urban groundwater systems, namely to assess the groundwater supply that might be available for non-potable practices, such as irrigation of parks and lawns, street cleaning and firefighting.

In recent years, a new focus on the scientific community has emerged, addressing issues on integrated studies on urban water supply systems, mainly in the largest old cities. In addition, urban hydrogeology, groundwater ecotoxicology, hydraulic and sanitary engineering, and geoarchaeological studies are fundamental to achieve a correct understanding of the overall outlook of the urban water systems. This integrative approach is far from being concluded, and research is still taking place. The sanitary and hydraulic engineer Harold F. Gray summarised this perspective in a remarkable way: *"If our progress today is so much less than what we know is possible, let us not be disheartened. Even though in four thousand years we have accomplished relatively little in sanitation, remember that after all that is but a small sector of time in man's history."* (Gray, 1940: 946).

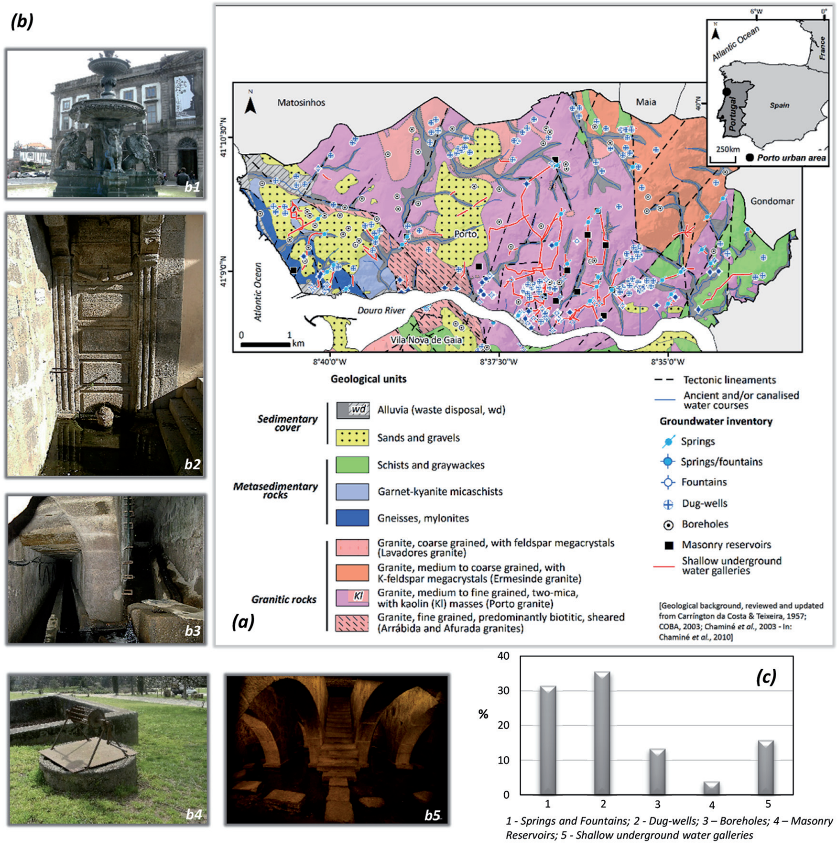


Figure 5: Current-day hydrogeological inventory in Porto urban area (GIS-mapping updated from Chaminé et al., 2010) (a) and several aspects of the water sample sites (b): b1 Leões fountain, b2 – Colher spring/fountain, b3 – Paranhos and Salgueiros underground water galleries; b4 – dug well, b5 – Arca d'Água masonry reservoir (photo kindly shared by Armando Bento); (c): groundwater inventory from the early 20th century to present (over 410 water sites).

Acknowledgements

This study was performed under the scope of the LABCARGA|ISEP re-equipment program (IPP-ISEP| PAD'2007/08) and Centre GeoBioTec|UA (PEst-C/CTE/UI4035/2014). Special thanks are due to Antónia Reis and Rafael Fernández-Rubio for kindly reviewing the French and Spanish version of the abstract, respectively. The authors would like to thank the reviewer for their helpful comments and input to improve the manuscript. We are grateful for all the support given by Herculano Ferreira ("Livraria Manuel Ferreira" antiquarian bookshop) by sharing some rare books about Porto city water studies. This paper is dedicated to the late Adriano Fontes, José Bahia Junior and José Carteado Mena from the Medical-Surgical School of Porto (Polytechnic Academy), who, under the guidance of Professor A. J. de Souza Junior, developed a set of outstanding dissertations dedicated to the issues of groundwater and water toxicology in the Porto urban area.

References

Afonso, M.J., Chaminé, H.I., Marques, J.M., Carreira, P.M., Guimarães, L., Guilhermino, L., Gomes, A., Fonseca, P.E., Pires, A., Rocha, F. 2010. Environmental issues in urban groundwater systems: a multidisciplinary study of the Paranhos and Salgueiros spring waters, Porto (NW Portugal). *Environmental Earth Sciences*, 61 (2). 379-392. DOI 10.1007/s12665-009-0351-7

Angelakis, A.N., Mays, L.W., Koutsoyiannis, D., Mamassis, N. 2012. *Evolution of water supply through the millennia.* IWA Publishing: London.

Bono, P., Boni, C. 1996. Water supply of Rome in antiquity and today. *Environmental Geology*, 27 (2). 126- 34. DOI 10.1007/BF01061685

Brody, H., Rip, M.R., Vinten-Johansen, P., Paneth N., Rachman, S. 2000. Map-making and myth-making in Broad Street: the London cholera epidemic, 1854. *The Lancet*, 356 (9223). 64-68. DOI 10.1016/S0140-6736(00)02442-9

Carríngton da Costa, J. 1938. O Pôrto: geografia-geologia. In: Bastos, C. (org.), *Nova Monografia do Porto, Companhia Portuguesa Editora*, Porto, p. 3-32

Chaminé, H.I., Afonso, M.J., Robalo, P.M., Rodrigues, P., Cortez, C., Monteiro Santos, F.A., Plancha, J.P., Fonseca, P.E., Gomes, A., Devy-Vareta, N., Marques, J.M., Lopes, M.E., Fontes, G., Pires, A., Rocha, F. 2010. Urban speleology applied to groundwater and geo-engineering studies: underground topographic surveying of the ancient Arca D'Água galleries catchworks (Porto, NW Portugal). *International Journal of Speleology*, 39 (1). 1-14. DOI 10.5038/1827-806X.39.1.1

EU [European Union] 2011. *Cities of tomorrow: challenges, visions, ways forward*. European Commission, Directorate General for Regional Policy: Brussels. DOI 10.2776/41803

Flint, A. 1873. Relations of water to the propagation of fever. *Public Health Papers and Reports*, 1. 164-172. ***http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2272680/***

Freitas, L., Afonso, M.J., Devy-Vareta, N., Marques, J.M., Gomes, A., Chaminé, H.I. 2014. Coupling hydrotoponymy and GIS cartography: a case study of hydrohistorical issues in urban groundwater systems, Porto, NW Portugal. *Geographical Research*, 52 (2). 182-197. DOI 10.1111/1745-5871.12051

Gray, H.F. 1940. Sewerage in ancient and medieval times. *Sewage Works Journal*, 12 (5). 939-946. ***http://www.jstor.org/stable/25029094***

Howard, K.W.F. 2014. Sustainable cities and the groundwater governance challenge. *Environmental Earth Sciences*, 12 p. (online first). DOI 10.1007/s12665-014-3370-y

Jackson, L. 2013. Maps and legends. *The Lancet*, 381 (9874). 1265-1266. DOI 10.1016/S0140-6736(13)60828-4

Koch, T. 2011. *Disease maps: epidemics on the ground*. The University of Chicago Press: Chicago and London

Lardner, W. 1833. The malignant cholera in Oporto. *The Lancet*, 20 (509). 300-302. DOI 10.1016/S0140-6736(02)94590-3

Lardner, W. 1855. History of the progress of the malignant cholera from Oporto to Lisbon. *The Lancet*, 23 (586). 314-320. DOI 10.1016/S0140-6736(02)96537-2

McCall, G.J., Demulder, E., Marker, B. 1996. *Urban geoscience*. AGID Special Publication Series, Vol. 20, Taylor & Francis: Rotterdam

Orton, E. 1874. Certain relations of geology to the water supplies of the country. *Public Health Papers and Reports*, 2. 292-305. ***http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2272500/***

Petitta, M. 2013. New challenges for hydrogeologists. *European Geologist*, 35. 6-8.

Pires de Almeida, M.A. 2012. The Portuguese *Cholera morbus* epidemic of 1853-56 as seen by the press. *Notes and Records of the Royal Society*, 66 (1). 41-53. DOI 10.1098/rsnr.2011.0001

Snow, J. 1855. *On the mode of communication of Cholera*. 2nd edition. John Churchill: London

Wittfogel, K.A. 1956. The hydraulic civilizations. In Thomas, W.L. (ed.), *Man's role in changing the face of the Earth*, The University of Chicago Press, Illinois. p. 152-164.

N° 38

November 2014

European Geologist

Journal of the European Federation of Geologists

Georchaeology - Reconstructing our early history