CHAPTER 20

Urban groundwater resources: a case study of Porto city in northwest Portugal

M.J. Afonso[1], H.I. Chaminé[1], J.M. Carvalho[1], J.M. Marques[2], A. Gomes[3], M.A. Araújo[3], P.E. Fonseca[4], J. Teixeira[5], M.A. Marques da Silva[5] and F.T. Rocha[5]

[1]*Dep. de Engenharia Geotécnica, Instituto Superior de Engenharia do Porto, Rua do Dr. António Bernardino de Almeida, 431, 4200-072 Porto, Portugal (E-mail: mja@isep.ipp.pt); and Centro de Minerais Industriais e Argilas (MIA), Universidade de Aveiro, Portugal*
[2]*Dep. de Engenharia de Minas e Georrecursos (DEMING), Instituto Superior Técnico, Lisboa, Portugal*
[3]*Dep. de Geografia (GEDES), Faculdade de Letras da Universidade do Porto, Portugal*
[4]*Dep. de Geologia (LATTEX), Faculdade de Ciências da Universidade de Lisboa, Portugal*
[5]*Dep. de Geociências, Universidade de Aveiro (MIA, ELMAS), Portugal*

ABSTRACT: Regional geological, morphotectonical and hydrogeological mapping in the sustainable management of groundwater resources is demonstrated for the Porto metropolitan area in northwest Portugal. Porto City is the second most important city on the Portuguese mainland and supports about 1 million inhabitants. Thirty-five groundwater samples collected from springs, dug-wells and boreholes were analysed for major ion parameters to investigate: i) their hydrochemical character, ii) their suitability for use and iii) the contaminant sources influencing water resource quality. The results obtained show that despite natural low level salinity derived from atmospheric transport of salts from the Atlantic Ocean, groundwaters underlying the Porto metropolitan area are generally suitable for both potable and irrigation uses. Locally, groundwater quality is compromised by human activities, most notably related to the intense urbanisation and local agricultural activities, the latter most predominant in the NW and NE sectors of the city.

1 INTRODUCTION

Urbanisation can have a profound effect on water resources and the hydrological cycle. The urban subsurface is a network of pipes, conduits, and other structures that serve to alter the natural hydraulic conductivity of the geologic materials. These features can also provide pathways for the movement of urban-sourced contaminants into underlying aquifers. A consequence of such complexities is that urban groundwater resources are frequently prone to uncontrolled exploitation and to degradation resulting from indiscriminate effluent and waste disposal practices (e.g. Legget, 1973; Foster, 1996; Custodio, 1997; Lerner, 1997; Morris et al., 1997; Foster et al., 1999). Research in earth sciences can help resolve such problems, but a common difficulty is that ground and surface water resources are rarely managed conjunctively despite their strong natural interdependence. Faced with increasing worldwide

pressure on water resources due to escalating demand, contamination and climatic change, it is becoming evident that integrated multidisciplinary approaches must be adopted to address the scientific issues related to water resources (e.g. Lerner, 1997; Morris et al., 1997; Aureli, 2002; Barrett, 2004).

This paper synthesises, from a multidisciplinary perspective, the nature and importance of surface water/groundwater interactions in the Porto metropolitan area of northwest Portugal. Porto city is the second most important city on the Portuguese mainland and supports about 1 million inhabitants in a 1000 km^2 area. The work is necessary to ensure that future demand for water resources can be met in the face of rapid urban, industrial, and agricultural growth. Local urban aquifers are recharged by meteoric waters and, under natural conditions this water discharges to local surface water systems or to the sea (Zaadnoordijk et al., 2004). The aquifers are recognised as vulnerable to depletion and contamination, and there is an urgent need to manage water resources in an equitable, sustainable, and ethical manner (e.g. Custodio, 1997; Barrett, 2004).

2 A BRIEF HISTORY

Porto City is located on sloping granitic hills on the banks of the Douro River, in Northern Portugal. It is one of the oldest cities in Europe and dates back to the days of the Suevi prior to the 6th Century, when it was known as *Portucale* (Harbour of Cale). It grew in importance following its conquest of 868 AD, eventually becoming the motivational centre behind the Christian re-conquest of the Iberian Peninsula (Oliveira Marques, 1972). Much of the original city was built in the 12th century and the architectural and historical attributes of its old neighbourhoods led Porto to be recognised by UNESCO as a World Heritage Site in 1996.

Until the end of the 13th century, most groundwater systems located across the Portuguese mainland could be considered natural, and had not been seriously degraded by human activity (Carvalho, 2001). Groundwater resources were utilised only locally, and where minor problems occurred they were generally resolved through natural regeneration. It was not until the turn of millennium (most notably, the last few decades of the 20th century), that groundwater resources became progressively more endangered, both in quantity and quality. The problem has been of particular concern in dense Southern Europe conurbations, such as those in the northern/central part of the Portuguese mainland where steep slopes leave little flat land suitable for urban development.

3 GEOMORPHOLOGICAL AND GEOTECTONICAL FRAMEWORK

The study area corresponds to the Porto metropolitan area, adjacent to the Atlantic Ocean. It is located in a complex geotectonic domain of the Iberian Massif, on the so-called Ossa-Morena Zone and Central-Iberian Zone boundary (Ribeiro et al., 1990), alongside the western border of the Porto–Tomar–Ferreira do Alentejo dextral major shear zone (Chaminé et al., 2003a,b; Ribeiro et al., 2003).

Topographically, the Porto region (*sensu latu*) is represented by a planar littoral platform dipping gently to the west and culminating around 120 masl (metres above sea level). To the east, the surface is bounded by a series of ridges ranging from 250 to 300 masl. Deeply incised river valleys interrupt the flatness of the surface, particularly the Douro river valley which is tectonically controlled. Evidence of neotectonic activity (Araújo et al., 2003)

includes: (a) numerous major faults affecting the uppermost fluvial deposits of the littoral platform and (b) outcrops of the same marine unit occurring at various elevations, forming an irregular pattern with a general trend dipping from north to south.

Several fractures cross the region; most are associated with the NNW-SSE set which dominates the region. A more discrete yet extensive fracture set oriented NE-SW has also been identified (Chaminé et al., 2003a; Araújo et al., 2003). Discontinuities are generally vertical to sub-vertical. In the latter fault system, dextral strike-slip faulting is associated with transpressive kinematics triggered by the post-orogenic collapse of the structure along the ancient Porto–Coimbra–Tomar thrust planes. These processes generated a multitude of ENE-WSW to NE-SW regional fault systems which provide tectonic control on the drainage network (Araújo et al., 2003) (Figure 1).

The regional geotectonic framework of the Porto metropolitan area (e.g. Sharpe, 1849; Delgado, 1905; Barata, 1910; Rosas da Silva, 1936; Carríngton da Costa, 1958; Oliveira et al., 1992; Almeida, 2001; Fernández et al., 2003; Chaminé et al., 2003a,b; and references therein) comprises a crystalline fissured basement complex which is strongly deformed and overthrusted by Late Proterozoic/Palaeozoic metasedimentary rocks and granites. The substratum complex is mainly composed of phyllites, black schists, garnetiferous quartzites, mica schists, migmatites and gneisses, whereas the sedimentary cover rocks are dominated by post-Miocene alluvial and Quaternary marine deposits. The igneous rocks include pre-orogenic and syn-orogenic Variscan suites, which comprise a large component of granitic rocks.

The crystalline bedrock of Porto city consists of granites in the eastern part and a gneiss-mica schist complex in the west (Figure 2). A major fault zone, Porto–Coimbra–Tomar shear zone (Chaminé et al., 2003a,b), trending NNW-SSE, defines the boundary between these two geological units. Variscan granitic rocks, representing the Porto granite facies and the Ermesinde porphyritic facies, underlie the Porto site (*s. str.*).

The Porto basement consists of a greyish (yellowish weathered surface) two-mica, coarse granite. The granite is generally weathered ranging from fresh-rock to residual soil up to depths of over 100 m (e.g. Begonha and Sequeira Braga, 1995; Begonha, 2001; Russo et al., 2001; Gaj et al., 2003; COBA, 2003). Most of the chemical palaeoweathering took place during Cenozoic times under tropical/subtropical conditions (Araújo et al., 2003).

4 REGIONAL HYDROGEOLOGY

The main hydrogeological subdivisions of the northern Portugal region are defined by the major active fault zones (e.g. Régua-Verin fault, Bragança-Manteigas fault, Porto–Coimbra–Tomar shear zone, Douro-Beira shear zone) (Brum Ferreira, 1991; Cabral, 1995; Chaminé et al., 2003a; Ribeiro, 2002). In the study area, the mean annual rainfall to the east of the Douro-Beira shear zone is over 1300 mm, but it is lower towards the coast, reaching 1150 mm in the urban area of Porto city (Afonso, 2003).

Hydrogeological data are scarce for the study area (see details in Afonso, 1997, 2003; Afonso et al., 2004, 2005), so the proposed regional hydrogeological classifications correspond broadly with the main geological features (Table 1):

(i) sedimentary cover (post-Miocene), including alluvium and fluvial deposits;
(ii) metasedimentary rocks (upper Proterozoic-Palaeozoic), which include schists, greywackes, quartz-phyllites and quartzites; and
(iii) granitic rocks (Variscan and/or pre-Variscan), including two mica granites, biotite granites; gneisses, migmatites and gneissic granites.

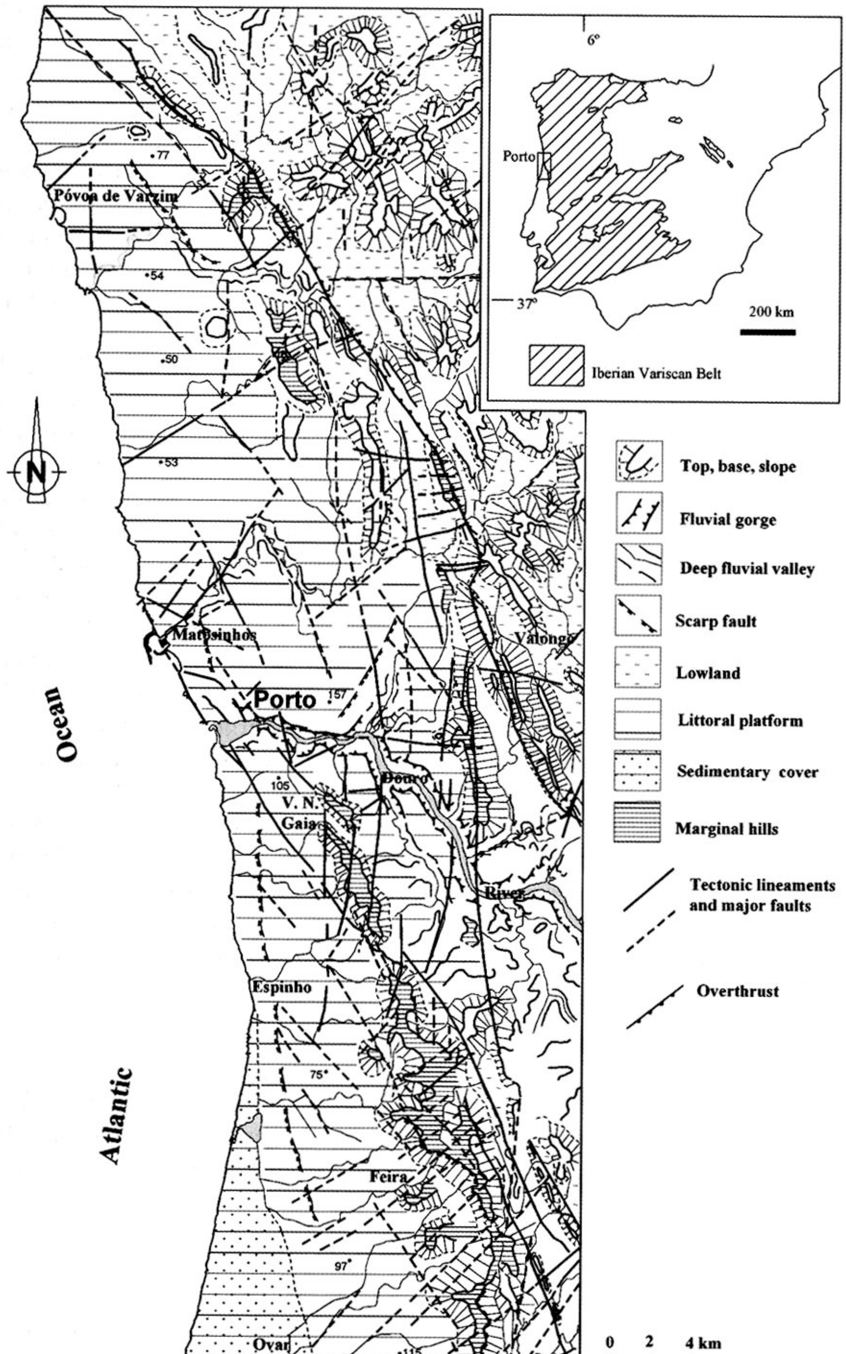

Figure 1. Morphotectonic features from the Porto metropolitan area (Póvoa de Varzim–Porto–Feira), NW Portugal (adapted from Araújo et al., 2003 and Chaminé et al., 2003a).

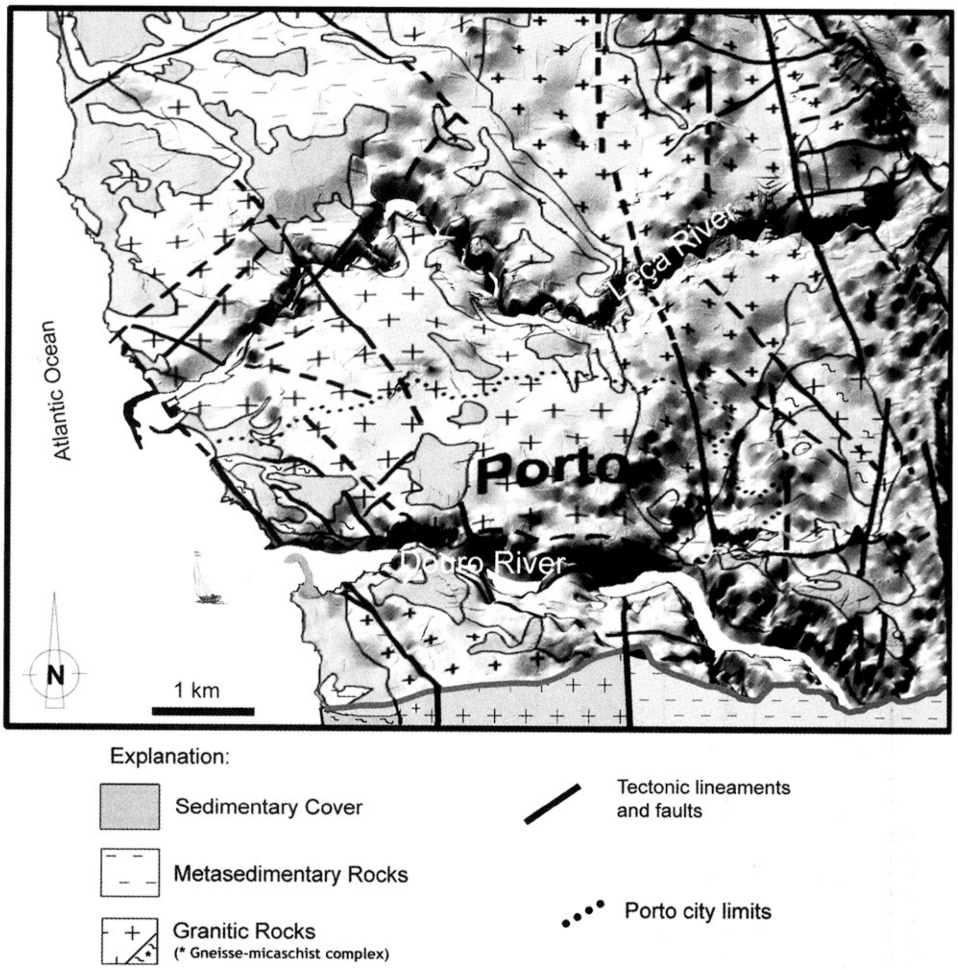

Figure 2. Digital elevation model (DEM) with an overlay of the geology for the Porto urban area (geological basement adapted from Chaminé, 2000; Araújo et al., 2003; Chaminé et al., 2003a). DEM of the studied area was generated by kriging digitized contour lines at a 1:25,000 scale. Ground resolution is 10 m. Shadowed image of the DEM is artificially illuminated from the west.

The geological, morphostructural and climatological conditions of the Porto metropolitan area strongly influence the distribution of groundwater resources (Carvalho, 1996; Monteiro, 1997; Carvalho et al., 2003, 2005). An assessment of regional hydrogeological units was carried out using the same lithological and structural framework used to define the regional geological units, and a regional hydrogeological map (Figure 3) was developed (Struckmeier and Margat, 1995; Assaad et al., 2004). Almost all aquifers in this region are associated with fissured hard rock and normally comprise weathered material that may extend to considerable depth. The zone of weathering has an important influence on the extent to which recharge reaches underlying aquifers.

Groundwater flowpaths are mainly governed by secondary permeability features such as faults, fractures and fissures, locally enhanced by weathering to produce discontinuous

Table 1. Regional hydrogeological units and related features in the Porto metropolitan area (see Figure 3).

Regional hydrogeological groups	Hydrogeological units	Hydrogeological features																
		Connectivity to the surface drainage network			Prevalent permeability		Weathering				More suitable exploitation structures		Geological risk of failure (MCI*, m/l/s)			Long-term well capacity (L/s)**		
		With	Without	Possible	Porous	Fissured	Low thickness	High thickness	Clayey	Sandy	Dug-wells, galleries and springs	Boreholes	Very high MCI > 120	High 80 < MCI < 120	Low MCI < 80	Very low Q < 1	Low 1 < Q < 2	High Q > 2
Sedimentary cover	Sands and alluvium	x			x		n.a.	n.a.	n.a.	n.a.	x				x		x	
	Sandstones and conglomerates	x			x		n.a.	n.a.	n.a.	n.a.	x				x		x	
Metasedimentary rocks	Quartz-phyllites, mica schists and black shales			x		x	x	x		x		x		x	x		x	
	Quartzites and slates		x	x		x	x			x		x		x	x		x	
	Schists, graywackes and metaconglomerates			x		x		x	x			x	x	x	x	x	x	
Granitic rocks	Granite, medium to coarse grain, with megacrystals			x		x		x		x	x		x	x		x		
	Granite, medium to fine grain, essentially biotitic			x		x		x		x	x		x	x		x		
	Gneisses and migmatites			x		x	x	x		x	x		x			x		

* MCI [Metres Capacity Index] in a given area, total drilled metres in one or several wells to obtain 1L/s; ** median long-term well capacity.

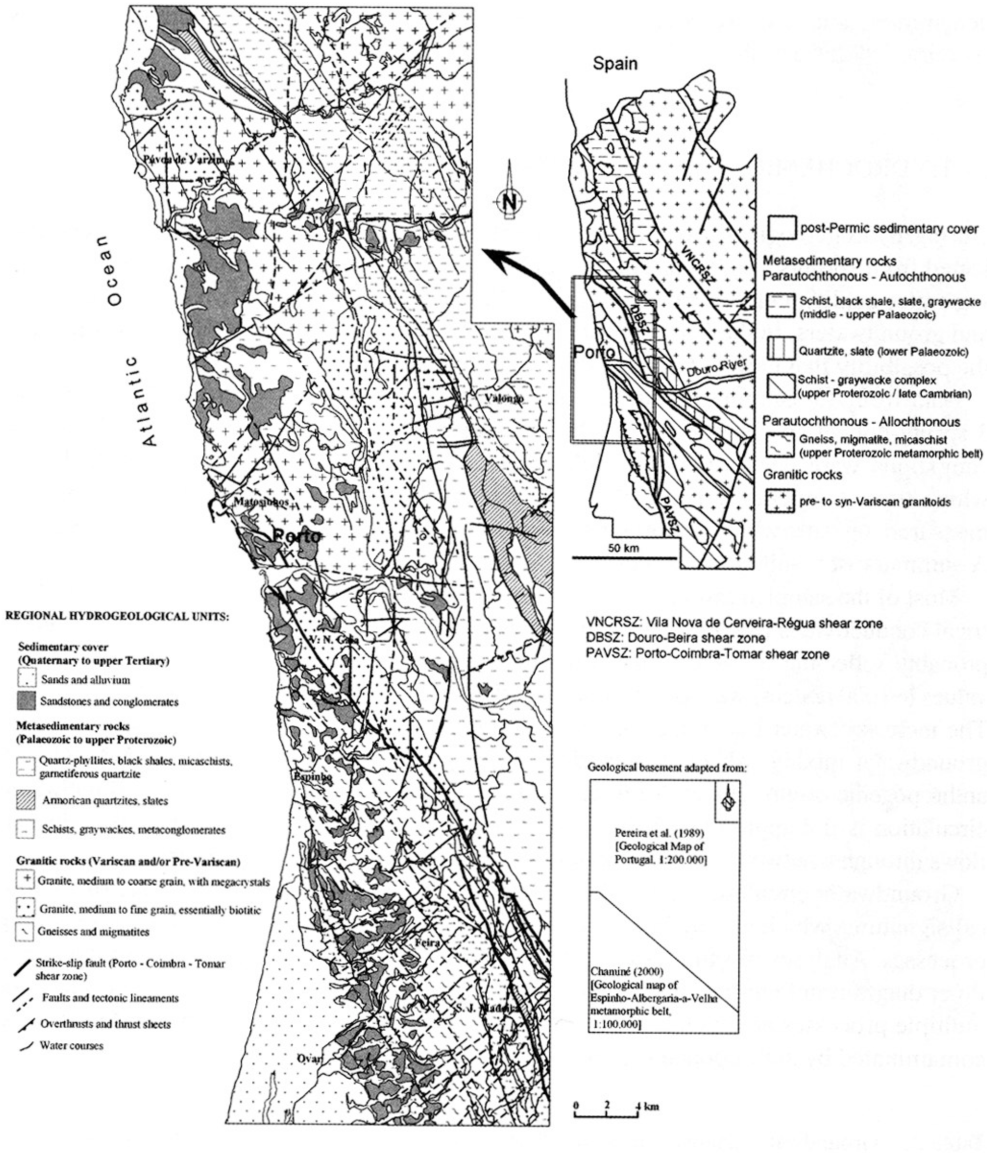

Figure 3. Regional hydrogeological outline from the Porto metropolitan area, northern Portugal (see Table 1 for hydrogeological features).

productive zones. While fracture connectivity is weak at the regional scale, it is nevertheless clear, that in the Variscan Iberian Massif, lithology and structure play a major role on the productivity of regional geological units and related water wells (Carvalho, 1996; Afonso et al., 2004; Carvalho et al., 2005). To assess well productivities, Carvalho (1993) and Carvalho et al. (2003, 2005) used data available from local well drillers to produce a Metres Capacity Index (MCI), defined for a given area as: MCI = Σ total drilled metres/ Σ total yield (L/s) for wells with long-term yields of >0.5 L/s. The MCI (see Table 1) is affected by the morphology, the thickness and nature of the weathering layer, the well

penetration, and the presence of filonian rocks (e.g. quartz veins) and fault gouges (Pereira, 1992; Carvalho, 1996).

5 HYDROCHEMICAL CLASSIFICATION OF GROUNDWATERS

During hydrogeological investigations of urban areas, chemical analyses of waters collected from springs, dug-wells and boreholes can provide important information concerning water quality, contaminant sources and the degree of mixing between surface waters and groundwaters. In the Porto city area a complicating factor is the adjacent coastline and the possibility that elevated groundwater salinity may be associated with the sea.

Data from 35 sampling points: 28 boreholes (mean depth of 103 m), 4 dug-wells and 3 spring-collection chambers. Sample locations are shown in Figure 4. Three fieldwork campaigns were performed (November, 1995, February, 1996 and July, 1996), during which time, temperature (°C), pH, electrical conductivity (μS/cm) and Eh (mV) were measured on site while major ions were analysed in samples sent to the laboratory. A summary of results for the February, 1996 study is presented in Table 2.

Most of the sampled groundwaters show near-neutral pH values and medium to low electrical conductivities (Figure 5). The highest pH values are mainly found in borehole waters, probably reflecting a higher interaction with the local geology. The highest conductivity values (~1000 μS/cm) were obtained during the February sampling program (Afonso, 1997). The increased water mineralisation noted during this time was indicative of surface water–groundwater mixing, whereby the surface water introduces ions (e.g. SO_4, Cl and NO_3) of anthropogenic origin. The use of water temperature as an indicator of depth of groundwater circulation is not appropriate here since, for many of the sampling sites, the groundwater flows through a network of pipes/conduits before arriving at the sampling point.

Groundwater circulating in the deeper granitic aquifers exhibits a wide range of chemical signatures which are difficult to explain simply on the basis of water-rock interaction processes. Analyses of samples collected during the July, 1996 campaign are plotted on a Piper diagram in Figure 6. The broad scatter of points, notably in the anion field, suggests multiple processes are operating including ion exchange and mixing with shallow waters contaminated by anthropogenic sources.

Table 2. Groundwater analyses from the Porto city area (February, 1996 fieldwork campaign). Concentrations in mg/L, temperature (T) in °C and electrical conductivity in μS/cm.

	No. of samples	Mean	Minimum	Maximum	Standard deviation
T	25	15.5	9.6	17.3	2.0
pH	25	6.13	4.55	7.45	0.62
Conductivity	25	489	201	1011	204
Na	25	43.9	9.1	103.0	20.6
K	25	6.7	2.0	16.2	4.3
Ca	25	29.3	5.6	60.8	13.5
Mg	25	10.6	1.5	22.8	5.5
HCO_3	25	58.6	2.4	125.7	33.4
Cl	25	62.9	10.6	188.5	38.5
SO_4	25	51.1	5.8	114.6	29.6
NO_3	25	38.4	0.8	138.6	38.2

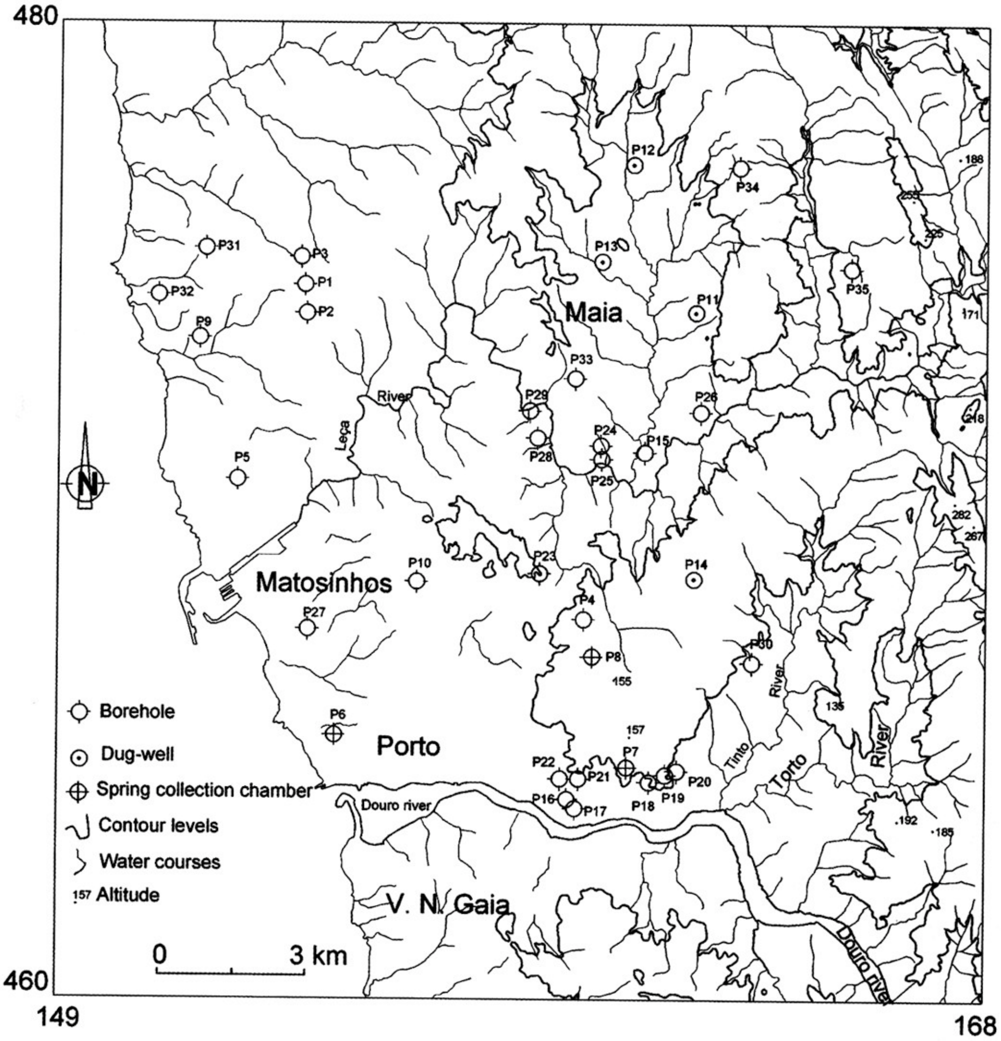

Figure 4. Location of the sampling points for hydrogeochemical analysis.

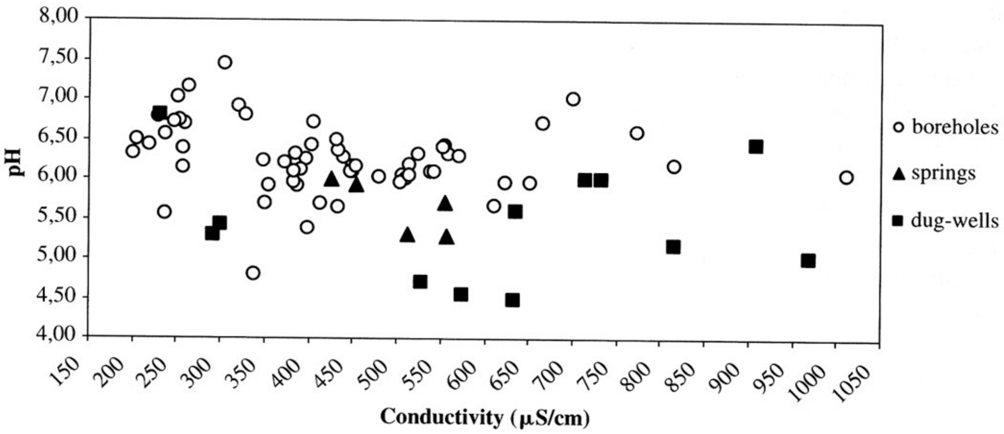

Figure 5. Conductivity *vs.* pH for water samples collected during the three fieldwork campaigns.

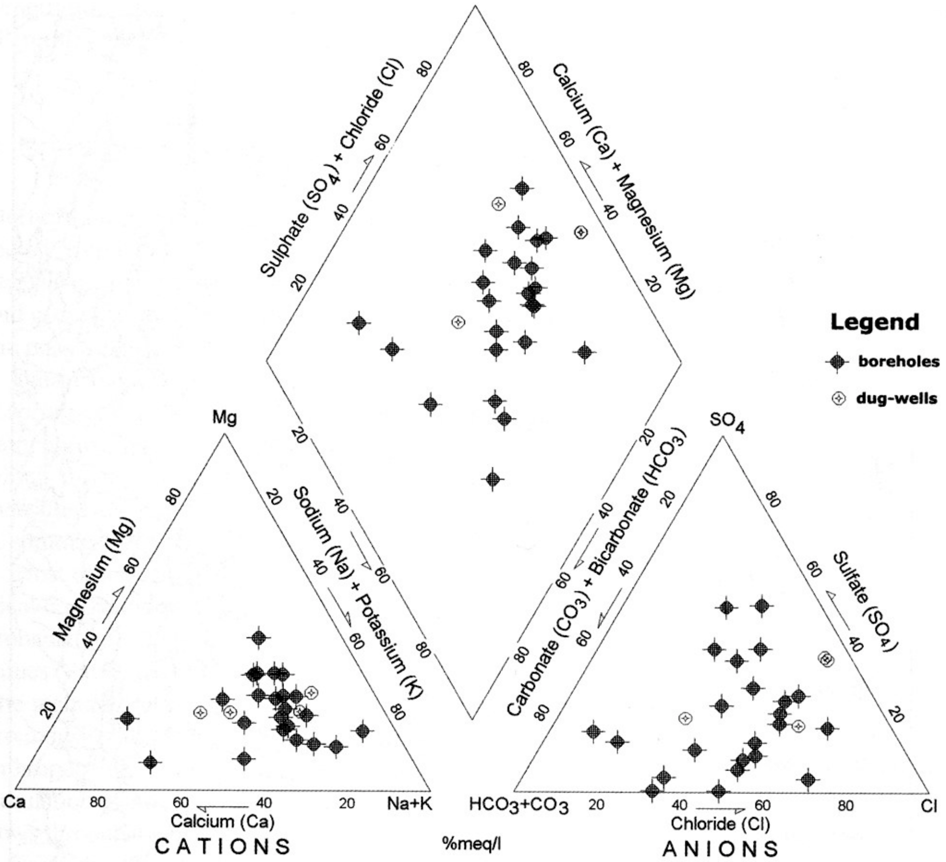

Figure 6. Piper diagram for water samples collected during the July, 1996 fieldwork campaign.

5.1 *Natural sources of mineralisation*

Natural sources of mineralisation include; (i) rock-water interaction and (ii) the airborne transport of salt from the adjacent Atlantic Ocean. Local hydrogeological conditions discourage the direct intrusion of seawater.

The atmospheric transport of sea spray is a well-known phenomenon in coastal areas. The droplets and evaporative particulates are transported by wind and deposited inland. Salt deposition is a function of topography and the exposure of the land surface to prevailing winds (Lorrai et al., 2004). Studies performed by Gustafsson and Franzén (2000) show that salt deposition rates decrease rapidly over the first 2–5 km from the coast, followed by a slower rate of reduction further inland.

Statistical and graphical analyses of the available data favour airborne salt deposition as the primary source of elevated sodium and chloride. For example, a weak correlation between HCO_3^- and Na^+ ($r = 0.17$) does not support the hydrolysis of plagioclase as a primary source of mineralisation, while a strong correlation between electrical conductivity and Na^+ ($r = 0.81$; data from July, 1996) and conductivity and Cl^- ($r = 0.75$; data from July, 1996), indicates a sodium chloride source.

Table 3. Chemical composition of rain waters (mean values) from the Porto region. Taken from Begonha et al. (1995) and Begonha (2001). Concentrations in mg/L.

HCO_3	Cl	SO_4	NO_3	PO_4	Na	K	Ca	Mg	NH_4	SiO_2
2.8	9.5	4.1	0.65	0.02	5.6	0.3	1.8	0.7	0.17	0.24

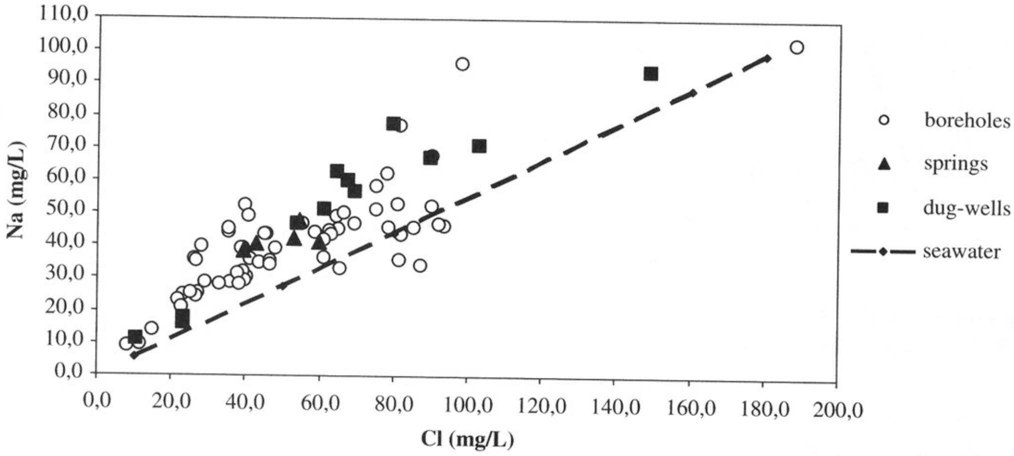

Figure 7. Cl *vs.* Na (mg/L) scatter diagram for groundwater samples collected during the three fieldwork campaigns within the Porto region.

Table 3 shows the chemical composition of rain waters from the Porto region. The ratio of Na to Cl in local precipitation is very close to the ratio found in seawater and is only slightly less than the ratio observed in much of the groundwater (Figure 7). After deposition of seawater salts in the soil zone, evaporation processes would be responsible for elevating the ion concentrations to those typically observed in the groundwater (Lorrai et al., 2004). The fact that the sodium concentration in the groundwater is slightly higher than would be expected from a pure NaCl source suggests that hydrolysis of plagioclase may provide an ancillary source of sodium.

5.2 *Groundwater contamination due to anthropogenic impacts*

Although groundwaters from the Porto city study area are of generally good quality and only slightly mineralised from natural processes, there is nonetheless evidence of anthropogenic pollution albeit, at relatively low levels. This is not unusual in rapidly growing cities which are host to numerous pollutant sources (Foster, 1997). Examples include:

- high nitrogen concentrations (normally nitrate, but sometimes ammonium) related to indiscriminate use of fertilizers, animal wastes and leaking sewer systems,
- high concentrations of chloride, commonly associated with waste water and landfills,
- high sulphate and borate concentrations, from detergents and construction waste,
- elevated dissolved organic carbon, and soluble manganese and/or iron and/or bicarbonate (as a result of oxidation of waste organic matter).

Ion scatter plots involving Ca^{2-}, SO_4^{2-} and Cl^- are shown (Figures 8 and 9, respectively) for the Porto city groundwater. Ca^{2+} and SO_4^{2-} are significantly elevated with respect to

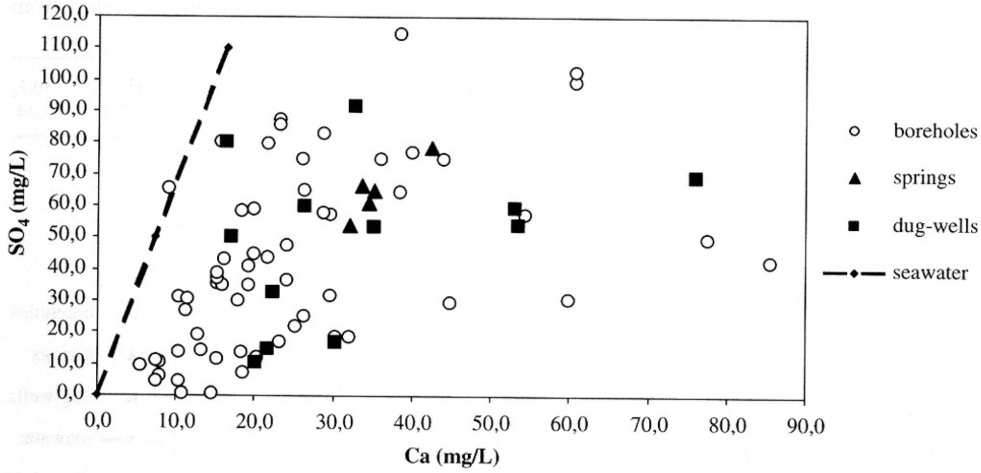

Figure 8. Ca *vs.* SO_4 (mg/L) scatter diagram for groundwater samples collected during the three fieldwork campaigns within the Porto region.

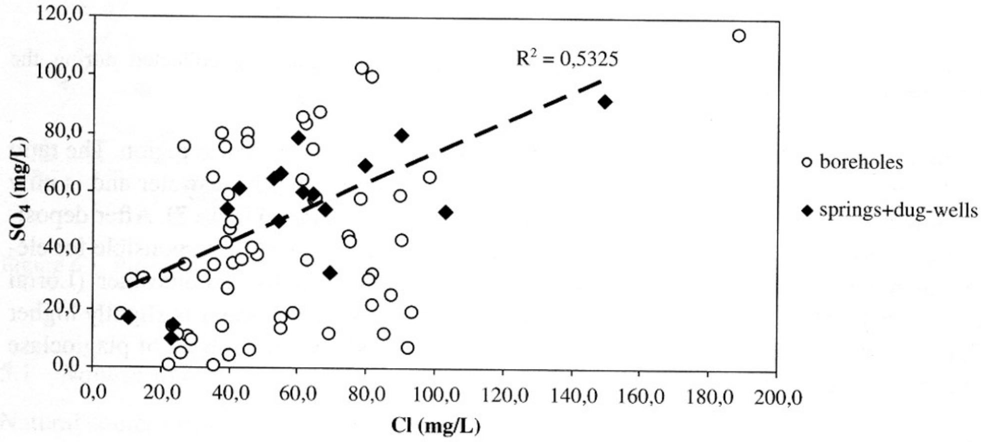

Figure 9. Cl *vs.* SO_4 scatter diagram for groundwater samples collected during the three fieldwork campaigns within the Porto region.

the concentrations anticipated from a simple seawater source, with SO_4^{2-}/Cl^- ratios in groundwater (commonly 1 to 1) being seven times higher than the ratio found in seawater (0.14 to 1) and Ca^{2+}/Cl^- ratios (typically 0.5 to 1) over twenty times higher than the ratio found in seawater (0.022 to 1). The probable source of sulphate, and to a lesser extent calcium, is air pollution (Aires-Barros, 1991; Begonha et al., 1995; Begonha, 2001) which is comprised of atmospheric gaseous SO_2 and particulate matter. SO_4^{2-}/Cl^- and Ca^{2+}/Cl^- ratios in local precipitation (Table 3) are approximately 0.5 to 1 and 0.2 to 1 respectively, which are significantly higher than ratios found in seawater, and approach the ratios found in Porto groundwater. Additional subsurface sources of calcium and sulphate found in solution may include construction waste containing gypsiferous material, although it should not

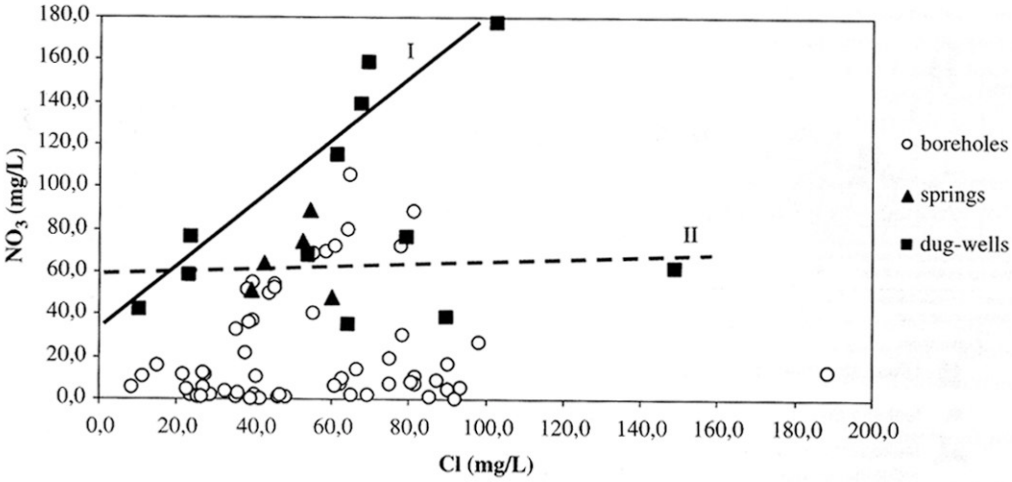

Figure 10. Cl *vs.* NO_3 scatter diagram for groundwater samples collected during the three fieldwork campaigns within the Porto region.

be discounted that the elevated calcium concentrations could also be partially attributed to ion exchange, the calcium being released from clays by the infiltration of sodium-rich water.

Finally, many of the Porto city groundwaters show elevated nitrate that in some cases exceed water quality guidelines. A Cl *vs.* NO_3 scatter plot is shown in Figure 10 and reveals two trends. Trend line I corresponds to the case where Cl and NO_3 are likely derived from the same source, and trend line II for which the Cl and NO_3 sources appear to be different. Typically, wastewater is a source of both Cl and NO_3 while sea water and agricultural fertilizer would be regarded as sole sources of the Cl and NO_3, respectively. Significantly, agricultural activity is relatively common in the NW and NE sectors of the city.

6 CONCLUSIONS

The value of regional geological, morphotectonical and hydrogeological mapping for the sustainable management of groundwater resources is demonstrated for the Porto metropolitan area in northwest Portugal. Hydrochemical studies involving major ion parameters were used to investigate (i) the hydrochemical character of groundwater resources, (ii) the suitability of groundwaters for use and (iii) the contaminant sources influencing water resource quality. A summary of conditions is shown in Figure 11. The results reveal that groundwaters underlying the Porto metropolitan area are slightly mineralised due to the atmospheric transport of salts derived from the nearby Atlantic Ocean and natural rock-water interaction. However, they are generally suitable for both potable and irrigation uses. Locally, groundwater quality is compromised by human activities which cause additionally elevated concentrations of calcium, sulphate nitrate and chloride. In some cases, concentrations of nitrate exceed the water quality guideline. The contamination is associated with the intense urbanisation and local agricultural activities, the latter most predominant in the NW and NE sectors of the city.

In the future, special emphasis will be put on integrating geochemical knowledge with isotopic analysis of precipitation and groundwater to increase the understanding of urban

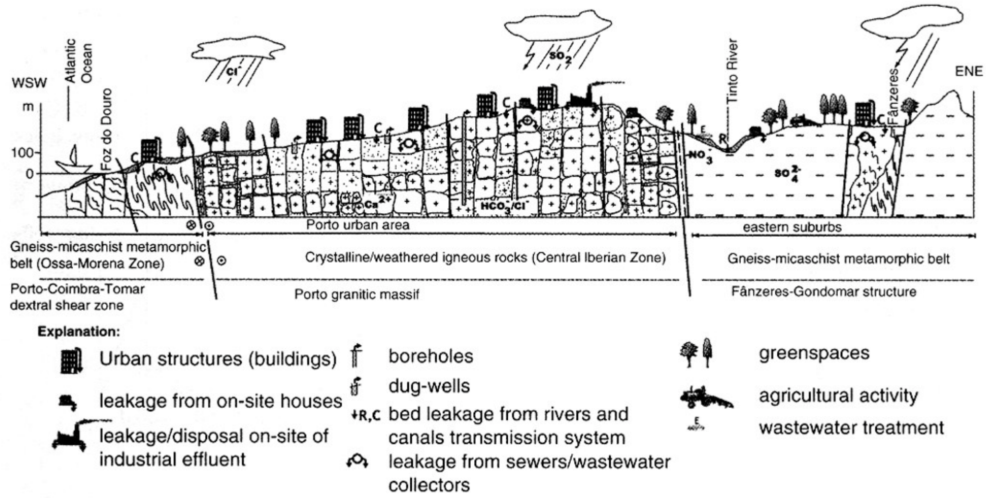

Figure 11. Conceptual hydrogeological cross-section illustrating the relationship of the main Porto city urban groundwater features (not to scale; geological and geomorphological background adapted from Chaminé et al., 2003a; Araújo et al., 2003).

water quality and quantity issues. The isotopic techniques to be employed include δ^2H and $\delta^{18}O$ for water and $\delta^{15}N$ and $\delta^{18}O$ for nitrate. In addition the vulnerability of groundwater sources will be assessed using environmental ^3H (Gonfiantini et al., 1998), and in some cases ^{14}C, thus allowing aquifer protection areas to be established.

ACKNOWLEDGEMENTS

This study was performed under the scope of the GROUNDURBAN (POCTI/CTE-GIN/59081/2004) project granted by the Portuguese Foundation for Science and Technology (FCT). This work was supported partially by grants from the GEODYN (POCTI-ISFL/5/32, Lisbon), FCT-SFRH/BPD/3641/2000 (Aveiro) and TBA (POCTI/CTA/38659/2001, Porto). We acknowledge Prof. Ken Howard and an anonymous reviewer for constructive reviews that helped to improve the clarity of the manuscript.

REFERENCES

Afonso, M.J.C. 1997. *Hidrogeologia de rochas graníticas da região do Porto.* Faculdade de Ciências da Universidade de Lisboa. 150 pp. (unpublished M.Sc. Thesis).

Afonso, M.J.C. 2003. Hidrogeologia de rochas graníticas da região do Porto (NW de Portugal). *Cadernos Laboratório Xeolóxico de Laxe*, A Coruña, 28: 173–192.

Afonso, M.J., Chaminé, H.I., Gomes, A., Teixeira, J., Araújo, M.A., Fonseca, P.E., Carvalho, J.M., Marques, J.M., Marques da Silva, M.A. and Rocha, F.T. 2004. Cartografia geológica e geomorfológica estrutural da área metropolitana do Porto: implicações na gestão dos recursos hídricos subterrâneos. *Xeográfica, Revista de Xeografía, Territorio e Medio Ambiente*, Santiago de Compostela, Spain, 4: 101–115.

Afonso, M.J., Espinha Marques, J., Marques, J.M., Carreira, P., Carvalho, J.M., Marques da Silva, M., Samper, J., Borges, F.S., Rocha, F.T., Fonseca, P.E., Gomes, A., Araújo, M.A., Teles Vieira, G.,

Mora, C., Teixeira, J., Almeida, P.G. and Chaminé, H.I. 2005. Hydrogeology of hard-rocks from two key-sectors in the Portuguese Iberian Massif: examples from Porto urban area and Serra da Estrela mountain region. In Lopo Ferreira, J.P. and Vieira, J. (eds.) *Proceedings The Fourth Inter-Celtic Colloquium on Hydrology and Management of Water Resources – Water in Celtic Countries: Quantity, Quality and Climate Variability*, Univ. Minho, Guimarães, LNEC-IAHS (Cd-Rom edition).

Almeida, A. 2001. Caracterização geoquímica e geocronológica do granito de duas micas sintectónico do Porto (NW de Portugal). In Lago, M., Arranz, E. and Galé, C. (eds.) *Proceedings III[er] Congreso Ibérico de Geoquímica/VIII Congreso de Geoquímica de España*. Instituto Tecnológico de Aragón, Zaragoza, pp. 311–315.

Aires-Barros, L. 1991. *Alteração e alterabilidade de rochas*. INIC, Lisboa. 384 pp.

Araújo, M.A., Gomes, A.A., Chaminé, H.I., Fonseca, P.E., Gama Pereira, L.C. and Pinto de Jesus, A. 2003. Geomorfologia e geologia regional do sector de Porto–Espinho (W de Portugal): implicações morfoestruturais na cobertura sedimentar cenozóica. *Cadernos Laboratório Xeolóxico de Laxe*, A Coruña, 28: 79–105.

Assaad, F.A., LaMoreaux, P.E., Hughes, T.H., Wangfang, Z. and Jordan, H. 2004. *Field methods for geologists and hydrogeologists*. Springer-Verlag. 420 pp.

Aureli, A. 2002. What's ahead in UNESCO's International Hydrological Programme? (IHP VI 2002–2007). *Hydrogeology Journal*, 10: 349–350.

Barata, J.M.P. 1910. *Contribuição para o estudo das rochas do Porto*. Faculdade de Philosophia Natural. Coimbra. 59 pp.

Barrett, M.H. 2004. Characteristics of urban groundwater. In Lerner, D.N. (ed.) *Urban groundwater pollution*, A.A. Balkema, Lisse, 24: 29–51.

Begonha, A. and Sequeira Braga, M.A. 1995. A meteorização do granito do Porto. In Borges, F.S. and Marques, M. (eds.) *IV Congresso Nacional de Geologia. Memórias Mus. Lab. Min. Geol. Fac. Ciênc. Univ. Porto*, 4: 171–175.

Begonha, A., Sequeira Braga, M.A. and Gomes da Silva, F. 1995. A acção da água da chuva na meteorização de monumentos graníticos. In Borges, F.S. and Marques, M. (eds.) *IV Congresso Nacional de Geologia. Memórias Mus. Lab. Min. Geol. Fac. Ciênc. Univ. Porto*, 4: 177–181.

Begonha, A. 2001. Meteorização do granito e deterioração da pedra em monumentos e edifícios da cidade do Porto. *Colecção monografias, FEUP Edições*, Porto, 2: 1–445.

Brum Ferreira, A. 1991. Neotectonics in Northern Portugal: a geomorphological approach. *Zeitschrift für Geomorphologie*, Berlin-Stuttgart, N.F., 82: 73–85.

Cabral, J. 1995. Neotectónica em Portugal Continental. *Memórias Inst. Geol. Min.*, Lisboa, 31: 1–256.

Carríngton da Costa, J. 1958. A geologia da região portuense e os seus problemas. *Boletim Academia Ciências Lisboa*, 30: 36–58.

Carvalho, J.M. 1993. Groundwater exploration in hard rocks for small scale irrigation in Trás-os-Montes, Portugal. In Sheila and David Banks (eds.) *Hydrogeology of hard rocks. Memoirs 24th Congress Int. Ass. Hydr.*, Oslo, 24(2): 1021–1030.

Carvalho, J.M. 1996. Mineral water exploration and exploitation at the Portuguese Hercynian massif. *Environmental Geology*, 27: 252–258.

Carvalho, J.M. 2001. As águas subterrâneas no abastecimento de núcleos urbanos no norte de Portugal. *Tecnologia da Água*, 4, 1: 4–18.

Carvalho, J.M., Chaminé, H.I. and Plasencia, N. 2003. Caracterização dos recursos hídricos subterrâneos do maciço cristalino do Norte de Portugal: implicações para o desenvolvimento regional. In *A Geologia de Engenharia e os Recursos Geológicos: recursos geológicos e formação. Volume de Homenagem ao Prof. Doutor Cotelo Neiva* (Portugal Ferreira, M., coord.), *Imprensa da Universidade, Série Investigação*, Coimbra, 2: 245–264.

Carvalho, J.M., Chaminé, H.I., Afonso, M.J., Marques, J.E., Medeiros, A., Garcia, S., Gomes, A., Teixeira, J. and Fonseca, P.E. 2005. Productivity and water cost in fissured-aquifers from the Iberian crystalline basement (Portugal): hydrogeological constraints. In López-Geta, J.A., Pulido Bosch, A. and Baquero Úbeda, J.C. (eds.) *Water, mining and environment Book Homage to Professor Rafael Fernández Rubio*. Instituto Geológico y Minero de España, Madrid, pp. 193–207.

Chaminé, H.I. 2000. *Estratigrafia e estrutura da faixa metamórfica de Espinho-Albergaria-a-Velha (Zona de Ossa-Morena): implicações geodinâmicas.* Faculdade de Ciências da Universidade do Porto. 497 pp. (unpublished PhD Thesis).

Chaminé, H.I., Gama Pereira, L.C., Fonseca, P.E., Noronha, F. and Lemos de Sousa, M.J. 2003a. Tectonoestratigrafia da faixa de cisalhamento de Porto-Albergaria-a-Velha-Coimbra-Tomar, entre as Zonas Centro-Ibérica e de Ossa-Morena (Maciço Ibérico, W de Portugal). *Cadernos Laboratório Xeolóxico de Laxe*, A Coruña, 28: 37–78.

Chaminé, H.I., Gama Pereira, L.C., Fonseca, P.E., Moço, L.P., Fernandes, J.P., Rocha, F.T., Flores, D., Pinto de Jesus, A., Gomes, C., Soares de Andrade, A.A. and Araújo, A. 2003b. Tectonostratigraphy of middle and upper Palaeozoic black shales from the Porto–Tomar–Ferreira do Alentejo shear zone (W Portugal): new perspectives on the Iberian Massif. *Geobios*, 36(6): 649–663.

COBA – Consultores de Engenharia e Ambiente, SA. 2003. *Notícia explicativa da Carta Geotécnica do Porto*. 2th edition, COBA/FCUP/Câmara Municipal do Porto, 230 pp.

Custodio, E. 1997. Groundwater quantity and quality changes related to land and water management around urban areas: Blessings and misfortunes. In Chilton et al. (eds.) *Proceedings of the 27th IAH Congress on Groundwater in the urban environment: Problems, processes and management*. Balkema, Rotterdam, 1: 11–22.

Delgado, J.F.N. 1905. Contribuições para o estudo dos terrenos Paleozóicos. *Comun. Comm. Serv. Geol. Portg.*, Lisboa, 6: 56–122.

Fernández, F.J., Chaminé, H.I., Fonseca, P.E., Munhá, J.M., Ribeiro, A., Aller, J., Fuertes-Fuentes, M. and Borges, F.S. 2003. HT-fabrics in a garnet-bearing quartzite from Western Portugal: geodynamic implications for the Iberian Variscan Belt. *Terra Nova*, 15(2): 96–103.

Foster, S. 1996. Groundwater quality concerns in rapidly-developing cities. In Guswa, J.H. (ed.) *Hydrology and hydrogeology of urban and urbanizing areas. American Institute of Hydrology,* St. Paul. pp. MIU12–MIU26.

Foster, S. 1997. The urban environment. Evaluation of hydrological changes and their consequences. *Proceedings of an International Symposium on Isotope Techniques in the Study of Past and Current Environmental Changes in the Hydrosphere and the Atmospher*e. International Atomic Energy Agency, Vienna, pp. 321–338.

Foster, S., Morris, B., Lawrence, A. and Chilton, J. 1999. Groundwater impacts and issues in developing cities: an introductory review. In Chilton, J. (ed.) *Proceedings of the 27th IAH Congress on Groundwater in the urban environment: Selected cities profiles*. Balkema, Rotterdam, 21: 3–16.

Gaj, F., Guglielmetti, V., Grasso, P. and Giacomin, G. 2003. Experience on Porto: EPB follow-up. *Tunnels and Tunnelling International*, pp. 15–18.

Gonfiantini, R., Frohlich, K., Araguás-Araguás, L. and Rozanski, K. 1998. Isotopes in groundwater hydrology. In Kendall and McDonnel (eds.) *Isotope tracers in catchment hydrology*, Elsevier, pp. 203–246.

Gustafsson, M.E.R. and Franzén, L.G. 2000. Inland transport of marine aerosols in southern Sweden. *Atmospheric Environment*, 34: 313–325.

Legget, R.F. 1973. *Cities and geology*. McGraw-Hill, New York. 579 pp.

Lerner, D.N. 1997. Too much or too little: recharge in urban areas. In Chilton et al. (eds.) *Proceedings of the 27th IAH Congress on Groundwater in the urban environment: Problems, processes and management*. Balkema, Rotterdam, 1: 41–47.

Lorrai, L., Fanfani, L., Lattanzi, P. and Wanty, R.B. 2004. Processes controlling groundwater chemistry of a coastal area in SE Sardinia (Italy). In Wanty and Seall II (eds.) *Proceedings of the International Symposium on Water-Rock Interaction*, 1: 439–443.

Monteiro, A. 1997. *O clima urbano do Porto: contribuição para a definição das estratégias de planeamento e ordenamento do território.* Colecção Texto Universitários de Ciências Sociais e Humanas. Fundação Calouste Gulbenkian/Junta Nacional de Investigação Científica e Tecnológica. 486 pp.

Morris, B.L., Lawrence, A.R. and Foster, S.D. 1997. Sustainable groundwater management for fast-growing cities: mission achievable or mission impossible? In Chilton, J. et al. (eds.) *Proceedings of the 27th IAH Congress on Groundwater in the urban environment: Problems, processes and management.* Balkema, Rotterdam, 1: 55–66.

Oliveira, J.T., Pereira, E., Ramalho, M., Antunes, M.T. and Monteiro, J.H. [coords.]. 1992. *Carta Geológica de Portugal escala 1/500000*, 5ª edição. Serviços Geológicos de Portugal, Lisbon.

Oliveira Marques, A.H. 1972. *History of Portugal. Vol. 1: from Lusitania to Empire*. Columbia University Press, New York. 507 pp.

Pereira, E., Ribeiro, A., Carvalho, G.S., Noronha, F., Ferreira, N. and Monteiro, J.H. [coords.]. 1989. *Carta Geológica de Portugal, escala 1/200000*. Folha 1. Serviços Geológicos de Portugal, Lisbon.

Pereira, M.R. 1992. Importância dos filonetes de quartzo na pesquisa de água subterrânea em rochas cristalinas. *Geolis*, Lisboa, 6(1/2): 46–52.

Ribeiro, A., Quesada, C. and Dallmeyer, R.D. 1990. Geodynamic evolution of the Iberian Massif. In Dallmeyer, R.D. and Martínez-García, E. (eds.) *Pre-Mesozoic Geology of Iberia*, Berlin, Heidelberg. Springer-Verlag. pp. 397–410.

Ribeiro, A. 2002. *Soft plate and impact tectonics*. Springer-Verlag, Berlin, Heidelberg. 324 pp.

Ribeiro, A., Marcos, A., Pereira, E., Llana-Fúnez, S., Farías, P., Fernandéz, F.J., Fonseca, P.E., Chaminé, H.I. and Rosas, F. 2003. 3-D strain distribution in the Ibero-Armorican Arc: a review. *Ciências da Terra (UNL)*, Lisboa, Nº Esp. V (CD-Rom, VI Congresso Nacional de Geologia): D62–D63.

Rosas da Silva, D.J. 1936. *Granitos do Porto.* Provas de Agregação, Porto. 63 pp.

Russo, G., Pescara, M., Kalamaras, G. and Grasso, P. 2001. A probabilistic approach for characterizing the complex geologic environment for design of the Metro do Porto. In Teuscher, P. and Colombo, A. (eds.) *Proceedings of the AITES-ITA 2001 World Tunnel Congress: Progress in tunnelling after 2000*, Milano, Italy. Pàtron Editore, Bologona, 3: 463–470.

Sharpe, D. 1849. On the Geology of the neighbourhood of Oporto, including the Silurian coal and slates of Vallongo. *Quart. Journ. Geol. Soc. London*, 5: 142–153.

Struckmeier, W.F. and Margat, J. 1995. Hydrogeological maps: a guide and a standard legend. *International Association of Hydrogeologists*, Hannover, 17, pp. 1–177.

Zaadnoordijk, W.J., van den Brink, C., van den Akker, C. and Chambers, J. 2004. Values and functions of groundwater under cities. In Lerner, D.N. (ed.) *Urban groundwater pollution*, A.A. Balkema, Lisse, 24: 1–28.

Urban groundwater – meeting the challenge

Selected papers from the 32nd International Geological Congress (IGC), Florence, Italy, August 2004

Matthias Eiswirth Memorial Volume

Edited by

Ken W.F. Howard
Vice-President of the International Association of Hydrogeologists (IAH), Chair of the IAH Commission on Groundwater in Urban Areas and Professor of Hydrogeology at the University of Toronto, Canada

Taylor & Francis
Taylor & Francis Group
LONDON / LEIDEN / NEW YORK / PHILADELPHIA / SINGAPORE

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS SELECTED PAPERS

8

Urban Groundwater - Meeting the Challenge

Editor: Ken W.F. Howard