CHAPTER 20

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


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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 km² 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. Custdio, 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 lato) 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; Carrington 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 over-thrust 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) (Brun 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-phylilitic 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).
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>
<thead>
<tr>
<th>Regional hydrogeological units</th>
<th>Hydrogeological features</th>
<th>Connectivity to the surface drainage network</th>
<th>Prevalent permeability</th>
<th>Weathering</th>
<th>More suitable exploitation structures</th>
<th>Geological risk of failure (MCI*, m³/s)</th>
<th>Long-term well capacity (L/s)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary cover</td>
<td>Sands and alluvium</td>
<td>x</td>
<td>x</td>
<td>n.a.</td>
<td>n.a.</td>
<td>Low MCI &gt; 120</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Sandstones and conglomerates</td>
<td>x</td>
<td>x</td>
<td>n.a.</td>
<td>n.a.</td>
<td>High MCI &lt; 120</td>
<td>x</td>
</tr>
<tr>
<td>Metasedimentary rocks</td>
<td>Quartz-phylites, mica schists and black shales</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Very high MCI &gt; 120</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Quartzites and slates</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>High MCI &lt; 120</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Schists, graywackes and metaconglomerates</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Low MCI &gt; 80</td>
<td>x</td>
</tr>
<tr>
<td>Granitic rocks</td>
<td>Granite, medium to coarse grain, with megacrystals</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Very low MCI &gt; 120</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Granite, medium to fine grain, essentially biotite</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>High MCI &lt; 120</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Gneissises and migmatites</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Low MCI &lt; 80</td>
<td>x</td>
</tr>
</tbody>
</table>

* 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.
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: \( MCI = \sum \text{total drilled metres} / \sum \text{total yield} (\text{L/s}) \) 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. SO₄, Cl and NO₃) 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.

<table>
<thead>
<tr>
<th></th>
<th>No. of samples</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>25</td>
<td>15.5</td>
<td>9.6</td>
<td>17.3</td>
<td>2.0</td>
</tr>
<tr>
<td>pH</td>
<td>25</td>
<td>6.13</td>
<td>4.55</td>
<td>7.45</td>
<td>0.62</td>
</tr>
<tr>
<td>Conductivity</td>
<td>25</td>
<td>489</td>
<td>201</td>
<td>1011</td>
<td>204</td>
</tr>
<tr>
<td>Na</td>
<td>25</td>
<td>43.9</td>
<td>9.1</td>
<td>103.0</td>
<td>20.6</td>
</tr>
<tr>
<td>K</td>
<td>25</td>
<td>6.7</td>
<td>2.0</td>
<td>16.2</td>
<td>4.3</td>
</tr>
<tr>
<td>Ca</td>
<td>25</td>
<td>29.3</td>
<td>5.6</td>
<td>60.8</td>
<td>13.5</td>
</tr>
<tr>
<td>Mg</td>
<td>25</td>
<td>10.6</td>
<td>1.5</td>
<td>22.8</td>
<td>5.5</td>
</tr>
<tr>
<td>HCO₃</td>
<td>25</td>
<td>58.6</td>
<td>2.4</td>
<td>125.7</td>
<td>33.4</td>
</tr>
<tr>
<td>Cl</td>
<td>25</td>
<td>62.9</td>
<td>10.6</td>
<td>188.5</td>
<td>38.5</td>
</tr>
<tr>
<td>SO₄</td>
<td>25</td>
<td>51.1</td>
<td>5.8</td>
<td>114.6</td>
<td>29.6</td>
</tr>
<tr>
<td>NO₃</td>
<td>25</td>
<td>38.4</td>
<td>0.8</td>
<td>138.6</td>
<td>38.2</td>
</tr>
</tbody>
</table>
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 $\text{HCO}_3^-$ and $\text{Na}^+$ ($r = 0.17$) does not support the hydrolysis of plagioclase as a primary source of mineralisation, while a strong correlation between electrical conductivity and $\text{Na}^+$ ($r = 0.81$; data from July, 1996) and conductivity and $\text{Cl}^-$ ($r = 0.75$; 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.

<table>
<thead>
<tr>
<th>HCO₃</th>
<th>Cl</th>
<th>SO₄</th>
<th>NO₃</th>
<th>PO₄</th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>NH₄</th>
<th>SiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>9.5</td>
<td>4.1</td>
<td>0.65</td>
<td>0.02</td>
<td>5.6</td>
<td>0.3</td>
<td>1.8</td>
<td>0.7</td>
<td>0.17</td>
<td>0.24</td>
</tr>
</tbody>
</table>

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 (Lorrain 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 Ca²⁺, SO₄²⁻ and Cl⁻ are shown (Figures 8 and 9, respectively) for the Porto city groundwater. Ca²⁺ and SO₄²⁻ are significantly elevated with respect to
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
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. NO₃ scatter plot is shown in Figure 10 and reveals two trends. Trend line I corresponds to the case where Cl and NO₃ are likely derived from the same source, and trend line II for which the Cl and NO₃ sources appear to be different. Typically, wastewater is a source of both Cl and NO₃ while sea water and agricultural fertilizer would be regarded as sole sources of the Cl and NO₃, 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
water quality and quantity issues. The isotopic techniques to be employed include δ²H and δ¹⁸O for water and δ¹⁵N and δ¹⁸O for nitrate. In addition the vulnerability of groundwater sources will be assessed using environmental ³H (Gonfiantini et al., 1998), and in some cases ¹⁴C, thus allowing aquifer protection areas to be established.

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