Urban hydrogeomorphology and geology of the Porto metropolitan area (NW Portugal)

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Abstract: Geoengineering multidisciplinary approaches probably offer the best potential for reliable surface and groundwater studies and the assessment of the variability in geospatial parameters, such as, lithological heterogeneity, structural geology features and geomorphology of a specific site. The Porto City was built in the 12th century and has been developed on granitic hill slopes of the Douro riverside, and is one of the oldest cities in Europe. In the urban area of Porto City, the second most important city of the Portuguese mainland, there is a human population of about 1 million.

Hydrogeological data acquisition in urban areas, in close connection with geological and geomorphological characteristics, is commonly, the key to predict the possible negative impacts of surface water / groundwater interaction. Most of the region is characterized by Variscan granitic rocks and a substratum of Upper Proterozoic and Palaeozoic metasedimentary rocks. The weathering of granitic rocks in this region results in arenisation, which may reach depths of more than 100 m.

This paper attempts to synthesise, under a multidisciplinary perspective, the surface water/groundwater interactions, including ecotoxicological aspects, in order to understand the Porto City urban environmental systems. In addition, the problems related to the requirements needed to meet the rapid expansion of urban, industrial, and agricultural water are also analysed. Urban aquifers, being crucial to local populations, are also the most susceptible to depletion and contamination. The intensity of impact will vary considerably according to the pollution vulnerability of underlying aquifers, the type and stage of urban development and the recharge rate. This paper demonstrates that the multidisciplinary approach proposed is quite adequate to understand urban hydrogeological processes and their dynamics. The role of urban geological, morphotectonical and hydrogeological mapping for the sustainable groundwater resources management of the Porto metropolitan area is described.

Résumé: Les approches multidisciplinaires de géo-ingénierie offrent probablement le meilleur potentiel pour les études d'eaux de surface et souterraines, et l'évaluation de la variabilité géospatiale de l'hétérogénéité lithologique et du cadre géologique et géomorphologique d'un lieu spécifique. La ville de Porto a été construite au 12ème siècle et développé sur les collines de la rive droite du fleuve Douro, étant l'une des plus anciennes villes d'Europe. Dans les secteurs urbains de la ville, la deuxième du pays, environ 1 million de personnes y habitent.

L'acquisition de données hydrogéologiques dans ces secteurs, en rapport avec des caractéristiques géologiques et géomorphologiques, est la plupart des cas la clef exclusive pour prévoir l'impact négatif provenant de l'interaction eaux de surface/eaux souterraines. La majeure partie de cette région est constituée par des granites Variscides et un substratum de roches metassédimentaires du Protérozoïque/Paléozoïque. L'altération des granites de cette région amène a l'arénisation, qui peut atteindre des profondeurs de plus de 100 m.

Cet article essaye de synthétiser, sous une perspective multidisciplinaire, les interactions eaux de surface/eaux souterraines, inclus les aspects écotoxicologiques, afin de comprendre les systèmes environnementaux urbains de la ville de Porto. En outre, les problèmes attribués à la nécessité d'accomplir les besoins de l'extension rapide des conditions urbaines, industrielles et agricoles de l'eau sont également analysés. Les couches aquifères urbaines, étant cruciales aux populations locales, sont aussi les plus susceptibles à l'épuisement et contamination. L'intensité de l'impact changera considérablement avec la vulnérabilité à la pollution des unités aquifères, le type et l'étape de développement urbain, et le taux de recharge. Cet article démontrera que l'approche multidisciplinaire proposée est tout à fait appropriée pour comprendre les processus hydrogéologiques urbains et sa dynamique. On montrera le rôle géologique, morphotectonique et hydrogéologique urbain sur la gestion de ressources soutenable d'eaux souterraines de la zone métropolitaine de Porto.

Keywords: geology of cities, geomorphology, hydrogeology, discontinuities, risk assessment, geoenvironmental engineering

INTRODUCTION AND OBJECTIVES

More than 50% of the world's population already live in cities and the proportion is rising extremely rapidly towards developed country levels of > 90%. Urbanization has a profound and often detrimental impact on the hydrological cycle at different scales. The urban subsurface includes a network of pipes, conduits and other structures that modify the natural hydraulic conductivity of the geological materials. Those structures were dug to facilitate transportation, drainage, sewerage and a water supply system for the population. Aquifers characterised by the presence of abundant, but vulnerable, groundwater are in many cases located below major cities, where the poor knowledge of aquifer characteristics, uncontrolled exploitation and indiscriminate effluent and waste disposal practices contribute to groundwater resources degradation (e.g., Legget 1973, Foster 1996, Custodio 1997, Lerner 1997, Morris *et al*. 1997, Foster *et al*. 1999, Chilton 1997, 1999, Aureli 2002).

Urban geology or urban geosciences can be described as an interdisciplinary field in geo- and socio-economic sciences addressing Earth-related problems in urbanised areas. Apart from the more traditional disciplines such as petrography, structural geology and geomorphology, some interdisciplinary fields such as engineering geology, hydrogeology and environmental geology play a dominant role in urban geosciences. The increasing worldwide pressure on water resources under conditions of global anthropogenic and climatic change often requires an integrated multidisciplinary approach to address the scientific issues involving water resources. Therefore, all these disciplines have to be integrated and incoporated with a thorough knowledge of the regional and local geological conditions, being more suitable for the human communities that make use of water and land in urban areas (Mulder *et al.* 2001). The hydrogeology of cities can be seen as a vital key to all successful urban planning. A city cannot exist without water and obtaining it in sufficient quantity and good quality, both for domestic and industrial use, is a primary civic service. Geology exercises critical control over most phases of water use and procurement so that, without adequate geological information, planning in respect of water cannot be carried out effectively (Legget 1973).

Groundwater conditions are also of primary significance in the construction and maintenance of subsurface engineering structures (e.g., tunnels, sewers, underground storage facilities and building foundation) and more generally in urban drainage (Barrett 2004). A reduction in the biological quality of groundwater is generally considered characteristic of groundwater abstracted from aquifers in or around urban areas. Although certainly not all geological hazards affecting cities can be attributed to the concentration of large masses of people in small areas, it is clear that many of the problems of today's major urban centres are directly or indirectly related to the geological and hydrological conditions beneath and around cities. Geological hazards may develop into artificially induced hazards, so the knowledge of geological and hydrogeological processes is essential to prevent and mitigate such hazards (Chilton 1997, 1999, Mulder *et al.* 2001).

Many of the issues in the present case study; the Porto metropolitan area, are strongly related to regional morphotectonics, palaeoweathering and biogeochemistry and climate framework. This work was undertaken within the scope of the *GROUNDURBAN* Project, of which the main goals can be summarised as follows (Figure 1).

- to adopt important technological capabilities to perform an integrated geoenvironmental multi-approach to water resources assessment;
- to update knowledge on the inter-relations between climate, hydrology and biology in urban areas
- to assess the quality and quantity of hydrogeochemical, isotopic geochemical and ecotoxicological parameters
- to characterise the main fissured geological and morphotectonical systems related to recharge and underground circulation
- to provide information to support water management and land use planning.

This study requires an integrated geoengineering multidisciplinary approach to understand the hydrogeological processes and their dynamics of groundwater resources from the study area. This paper also attempts to synthesise the surface water / groundwater interactions in order to understand these environmental urban systems. In addition, the necessity to meet the rapidly expanding urban, industrial, and agricultural water requirements is also analysed.

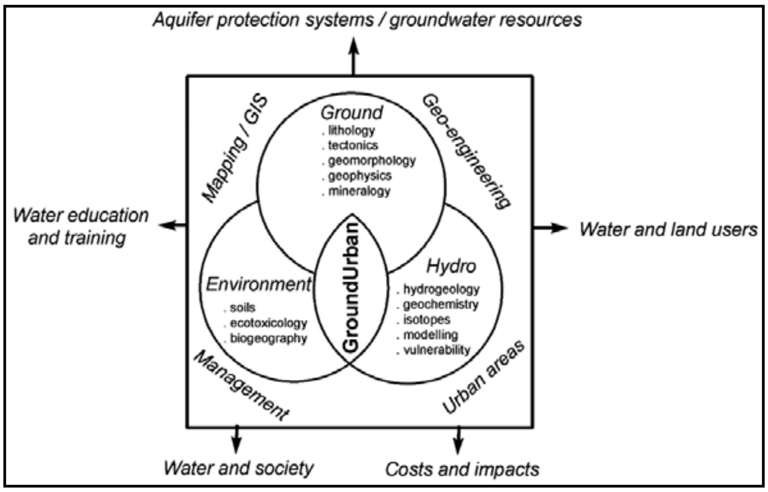

Figure 1. Conceptual framework for the management and protection of urban groundwater resources: the *GROUNDURBAN* project.

PORTO METROPOLITAN AREA: AN OVERVIEW

Water management decisions may influence aquifers in dense urban areas. This is especially true in the dense Southern Europe conurbations, particularly in the Northern/Central part of Portuguese mainland, in which the steep topography leaves scarce flat land for town development. Until the end of the 19th century, the natural conditions of most groundwater systems located in Portuguese mainland had not been seriously degraded by human intervention (Carvalho 1996). These resources were utilised only locally, and these effects were generally compensated by natural regeneration. However, at the turn of the millennium, and especially in the last few decades of the 20th century, these resources have become progressively more endangered, both in quantity and quality.

Brief history of the Porto city

The metropolitan area of Porto is the second biggest urban area in Portugal. The area covered by this region is almost 1600 km^2 and nowadays there are about 1.5 million inhabitants. Porto city is the capital of this region, having an area of ca. 42 km^2 and a population of 260,000 inhabitants. This conurbation is the second largest city in Portugal mainland and is located on the banks of the Douro River, near the Atlantic Ocean. Being one of the oldest cities in Europe, the history of Porto city dates back at least to the 6th century, since the days of the Suevians, Vandals and Visigoths. The conquest of the so-called *Portucale*, the previous designation for the Porto area, in 868 A.D. is duly considered as an event of the most ancient history of Porto. However, as of 868 A.D. it became the centre of the movement of Christian's re-conquest of Iberian Peninsula (Oliveira Marques 1972). The Porto city became an important conurbation since the 12th century and has been developed on granitic hill slopes of Douro riverside. The old neighbourhoods, bearing a striking picture of architectural and historical attributes of Porto city, led to its recognition by UNESCO as a World Heritage Site in 1996.

Structural geology and geomorphological setting

Porto metropolitan area is located in a complex geotectonical 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).

The geomorphologic configuration of this region (Figure 2) consists of a littoral platform characterised by a quite regular planation surface dipping gently to the West, culminating around 120m a.m.s.l., and to the East is bounded by a series of hill ridges (250-300m a.m.s.l. on the top). Deeply incised river valleys interrupt the flatness of this surface, particularly the Douro river valley, which is controlled by the regional tectonic fabric. There is abundant evidence for tectonic activity, such as a large number of significant, mainly reverse faults affecting the higher fluvial deposits of this littoral platform and also the same marine equivalent level outcrops seem to appear at different altitudes, developing a non correlative pattern with a general trend dipping from the North to the South (Araújo *et al*. 2003).

The regional fracture network defines some preferential orientations (Chaminé *et al*. 2003a, Araújo *et al*. 2003). NNW-SSE is dominant, and more discreetly, NE-SW; while the predominant dip of the faults is vertical to sub-vertical. During the late Cenozoic, a strike-slip faulting pattern resulted in 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 discrete ENE-WSW to NE-SW regional fault systems. The drainage network reveals this tectonic control, which imposed morphostructural features to the area (Figure 2).

The regional structural framework of Porto metropolitan area (Sharpe 1849, Rosas da Silva 1936, Carríngton da Costa 1938, 1958, Araújo *et al*. 2003, Chaminé *et al*. 2003a,b, and references therein) comprises a crystalline fissured basement complex which is strongly deformed and overthrusted Late Proterozoic and Palaeozoic metasedimentary rocks and granites. The substratum complex is mainly composed of phyllites, black schists, garnetiferous quartzites, micaschists, migmatites and gneisses, whereas 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 occupy a large exposure of granitic rocks (Figure 3).

Hydrogeological framework

The role of the regional structural geology and geomorphology mapping on the sustainable groundwater resources management of the Porto metropolitan area is described. The regional hydrogeological units described in Porto metropolitan area are presented in Table 1.

The negative impact on the quality of groundwater resources can take considerable time to be detected, since the response time of groundwater systems is the longest of all components of the urban hydrological cycle. Thus, in these areas, hydrogeological data acquisition namely structural, morphotectonical and geological, is, generally, the key to predict the possible negative impacts of surface water–groundwater interaction (Figure 4). The intensity of the impacts is usually dependent on the vulnerability to pollution of underlying aquifers and directly connected with the type and stage of urban development.

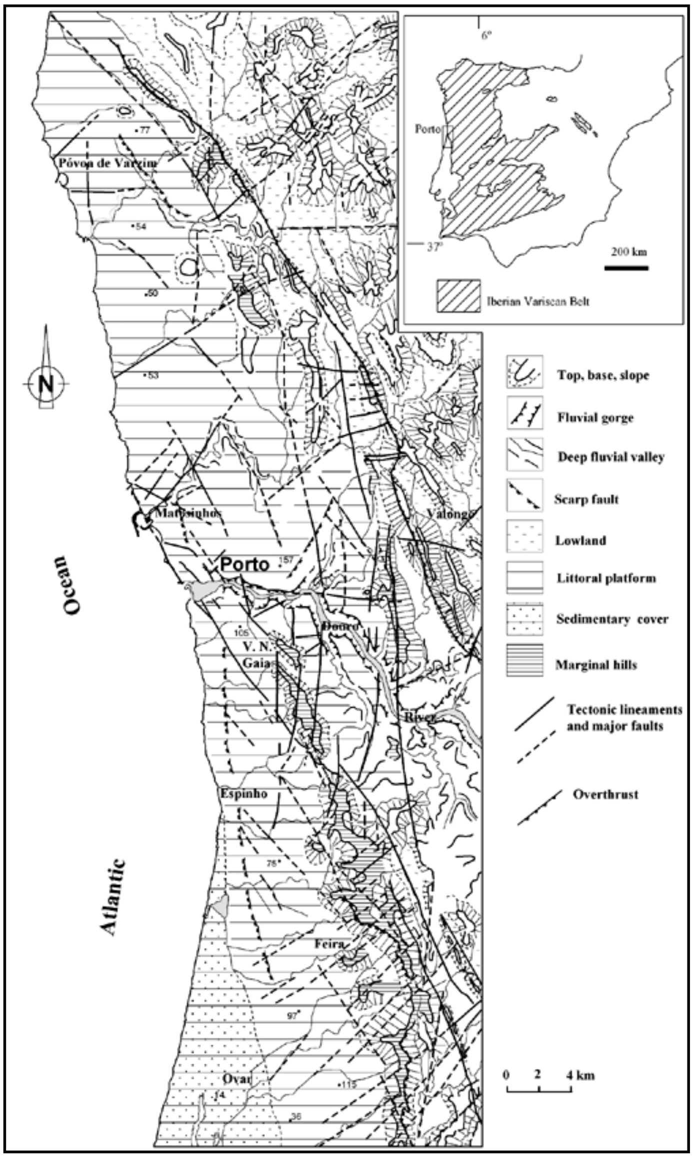

Figure 2. Morphotectonic features from the Porto metropolitan area (Póvoa de Varzim – Porto – Feira), NW Portugal (adapted from Afonso *et al.* 2004).

Table 1. Regional hydrogeological units and related features in the Porto metropolitan area.

Regional Hydrogeological Groups	Hydrogeological Units	HYDROGEOLOGICAL FEATURES										
		Connectivity to the drainage network			Type of flow		Weathering				More suitable exploitation structures	
		with	without	possible	porous medium	fissured medium	low thickness	high thickness	clayey	sandy	dug-wells, galleries and springs	boreholes
Sedimentary cover	sands and alluvium	x			x		n. a.	n. a.	n. a.	n. a.	x	
	sandstones and conglomerates	x			x		n. a.	n. a.	n. a.	n. a.	x	
Metasedimentary rocks	quartz-phyllites, micaschists and black shales			x		x	x	x		x		x
	quartzites and slates		x	x		x	x			x		x
	schists, graywackes and metaconglomerates			x		x		x	x			x
Granitic rocks	granite, medium to coarse grain, with megacrystals			x		x		x		x	x	
	granite, medium to fine grain, essentially biotitic			x		x		x		x	x	
	gneisses and migmatites			x		x	x	x		x	x	

n.a.= not applicable

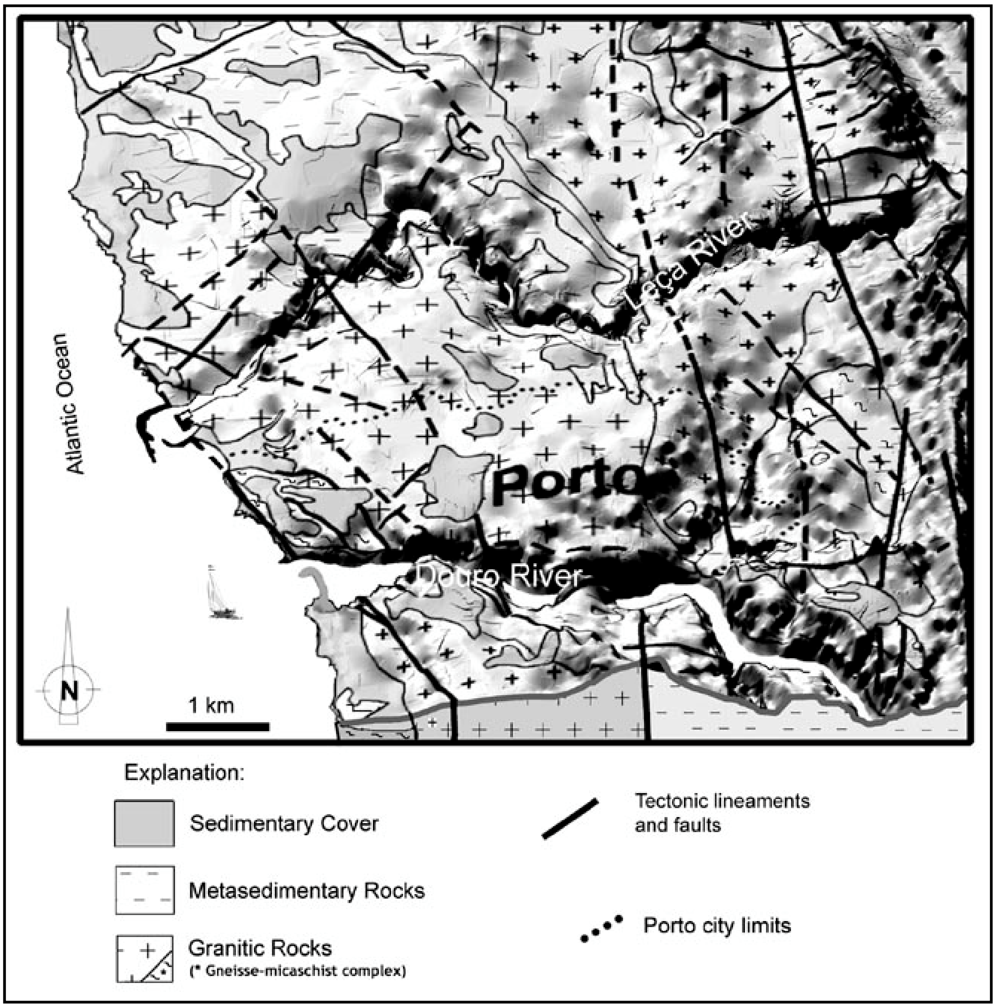

Figure 3. Geological digital elevation model (DEM) of the Porto urban area (geological basement adapted from Chaminé 2000, Araújo *et al.* 2003, Chaminé *et al.* 2003a). DEM of the studied area was generated by kriging digitized contour lines at a 1:25.000 scale. Ground resolution is 10m. Shadowed image of the DEM artificially illuminated from the West.

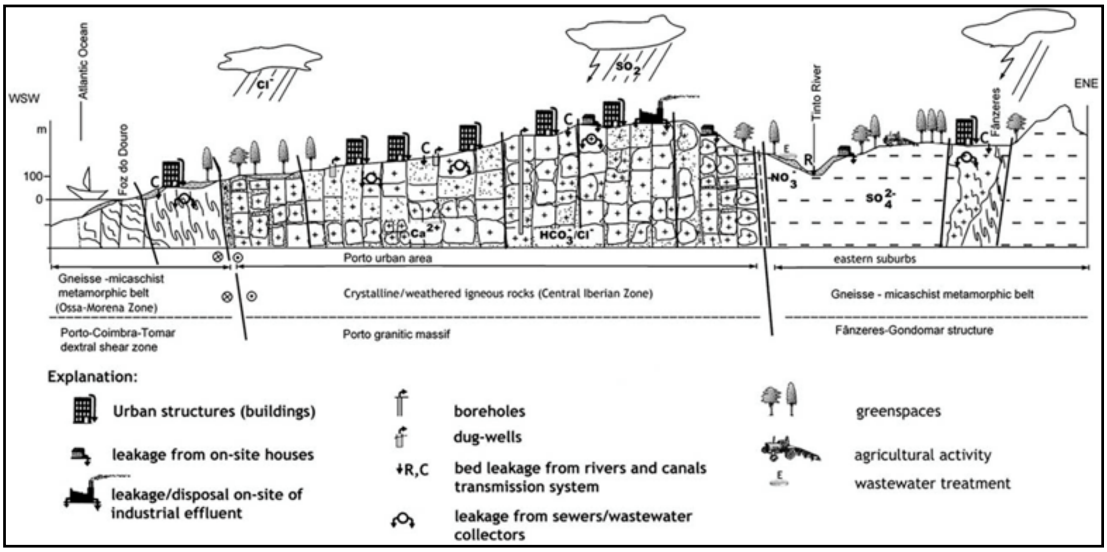

Figure 4. Conceptual hydrogeological cross-section illustrating the relationship of the main Porto city urban groundwater features (not to scale; geological and geomorphological background adapted from Chaminé *et al.* 2003a, Araújo *et al.* 2003).

PARANHOS SPRING COLLECTION CHAMBERS: A CASE STUDY IN PORTO CITY

For more than five centuries, the water supply of Porto city was derived from fountains which were fed by numerous springs (*e.g.*, Bourbon e Noronha 1885, Ferreira da Silva 1889, Fontes 1908, SMAS 1961, Amorim & Pinto 2001, Afonso 2003). Several underground galleries were excavated throughout the centuries to collect the water from these springs. Paranhos spring collection chambers constituted one of the main galleries (Figure 5).

This work presents a multidisciplinary approach to preliminary characterization of the bedrock of Porto city, in order to assess its nature and suitability for use of groundwater from spring collection chambers located in this urban area. For that purpose, the underground area (*ca.* 3km long and at a maximum depth of –20m below ground level) was studied using the following tools: subsurface geological and geotechnical mapping (scale: 1:1000), structural geology, geotechnical/geomechanical, hydrogeological and ecotoxicological techniques (*e.g.*, UNESCO 1976, ISRM 1978, 1981, IAEG 1981a,b, Struckmeier & Margat 1995, GSE 1995, CFCFF 1996, Cooney 1995, OCDE 2000, Walker *et al.* 2001, Assaad *et al.* 2004, IAEG 2005, Mandl 2005).

For the structural geology and geotechnical characterisation, the scanline sampling technique of discontinuities (e.g., ISRM 1978, 1981, Hudson & Priest 1993, Peacock, Harris & Mauldon. 2003, Brady & Brown 2004) has been applied to the deformed granitic rock-masses faces from Paranhos spring galleries. Surface and subsurface fieldwork surveys were first carried out to identify major tectonic events responsible for groundwater circulation paths, and to assess lithological and structural heterogeneity. The results achieved at different scales were compared in order to detect the presence of a multiscale fracture network patterns.

The crystalline bedrock of Porto city consists mainly of granitic rocks, representing the so-called Porto granite facies (Almeida 2001, Chaminé *et al.* 2003a). It is medium to coarse grained, deformed, greyish in colour, changing to yellowish when weathered and includes two-mica minerals. The granitic facies are generally weathered to different grades, from fresh-rock to residual soil, showing highly variable conditions, resulting in arenisation and kaolinisation, which may reach depths of more than 100m (e.g., Begonha 2001, Gaj *et al*. 2003, COBA 2003). The local fracture network is intense and defines some preferential orientations of NNE-SSW to NE-SW, namely N20º-30ºE, with a dip of 70º-80º towards the NW. Several fault sets were also recognised with a mean orientation of NE-SW, N-S and a sub-horizontal set.

In what concerns the hydrogeological and ecotoxicological fieldwork campaigns, several sampling sites were selected. Temperature (ºC), pH and electrical conductivity (µS/cm) were evaluated *in situ* and water samples were collected in these galleries both for hydrochemical and ecotoxicological analyses. All water samples have been analysed for major element concentrations. For ecotoxicological evaluation standard bioassays with *Daphnia magna* were performed (ASTM 1980, OCDE 2000). Preliminary hydrochemical analyses showed a nitrate and sulphate-enriched composition for these groundwaters, probably resulting from intense urbanisation, sewer leakage and some agricultural practices. Concerning the ecotoxicological analyses, no mortality was observed in any of the tests performed (Guimarães *et al.* 2005). These results suggest that part of Porto urban groundwater can be suitable for irrigation uses, but additional tests must be carried out to verify its compliance with existing standards of quality. Specifically, geoenvironmental and ecotoxicological studies are required to assess potential variations in water composition and toxicity associated with seasonal changes in climate and human activities.

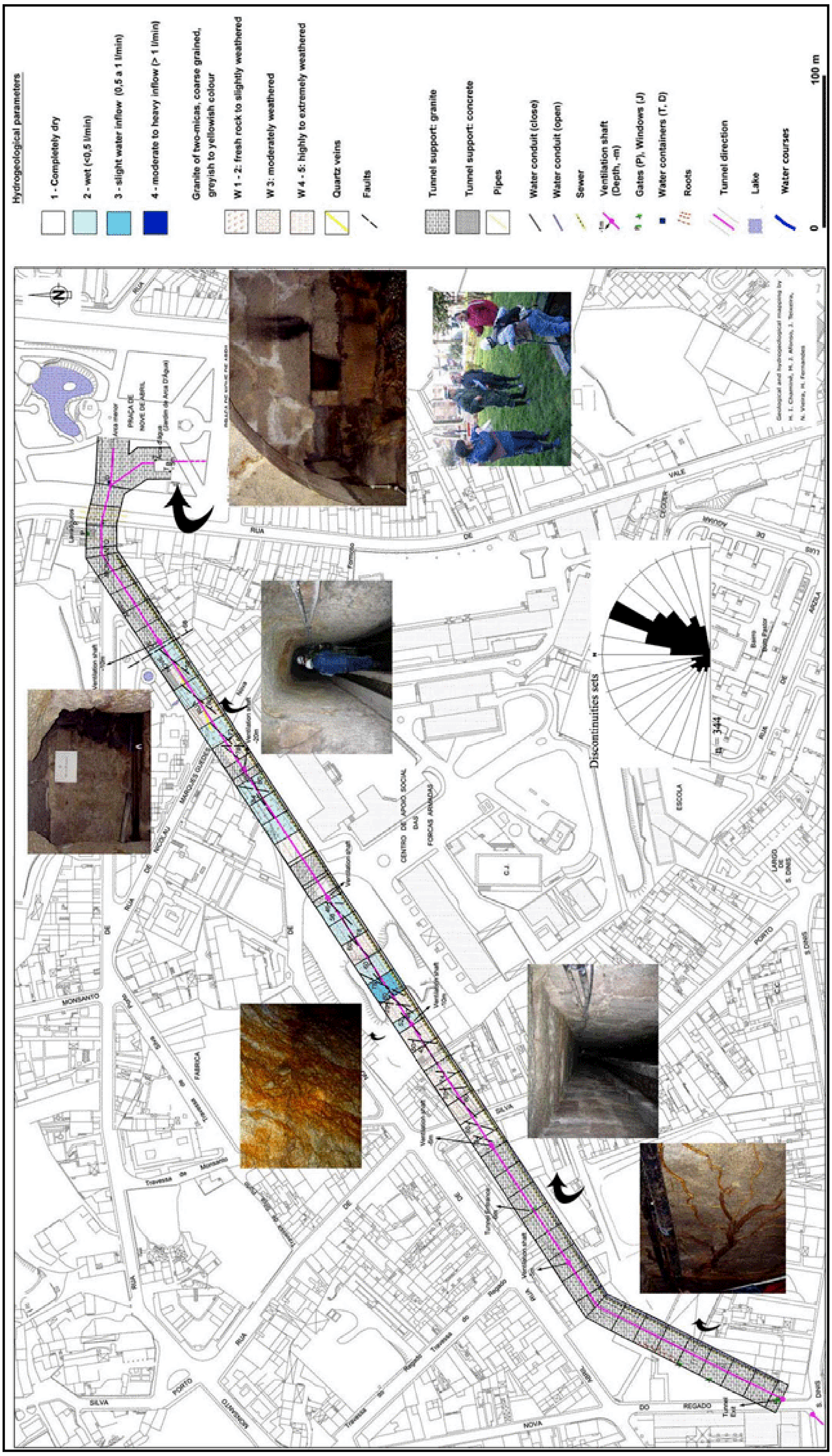

Figure 5. Geological and hydrogeological mapping of one sector of Paranhos' galleries.

CONCLUDING REMARKS

Characterisation of groundwater resources in urban areas seeks to address several important questions related to the sustainable management of local and regional groundwater resources. This usually provides important methodologies and tools to assess the interaction between surface/ground waters, supporting prevention and mitigation of possible environmental problems. Geoengineering multidisciplinary approaches probably offer the best potential for reliable groundwater and surface water studies and for assessment of the variability in geospatial parameters, such as, lithological heterogeneity, structural geology, geomorphology and geotechnics of a specific site. So, the combination of consistent local data, remote sensing and GIS technology offers promise for a better understanding over large urban areas.

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