CHAPTER 16

Vadose zone characterisation of a hydrogeologic system in a mountain region: Serra da Estrela case study (Central Portugal)

Jorge Espinha Marques[1], João M. Duarte[2], Alfredo T. Constantino[2], Afonso Martins[3], Carlos Aguiar[4], Fernando T. Rocha[5], Manuela Inácio[5], José M. Marques[6], Helder I. Chaminé[7,5], José Teixeira[5], Javier Samper[8], Frederico S. Borges[1] & José M. Carvalho[7]
[1]*Dep. Geologia (CGUP), Univ. Porto, R. Campo Alegre Porto, Portugal*
[2]*Agroconsultores, Lda., Lisbon, Portugal*
[3]*Dep. Edafologia, UTAD, Apartado Vila Real, Portugal*
[4]*Centro de Investigação da Montanha (CIMO), IPB, ESA, Bragança, Portugal*
[5]*Centro de Minerais Industriais e Argilas (MIA), Univ. Aveiro, Aveiro, Portugal*
[6]*Dep. Eng^a Minas Georrecursos, IST, Av. Rovisco Pais, Lisbon, Portugal*
[7]*Dep. Eng^a Geotécnica, ISEP, Porto, Portugal*
[8]*ETSI Caminos, Canales y Puertos, Univ. Coruña, Campus Elviña, Spain*

ABSTRACT: Understanding the role of the vadose zone is essential to accurately assess hydrogeological systems and their respective groundwater resources. The study area (Manteigas – Nave de Santo António – Torre sector, *Serra da Estrela* Mountain, Central Portugal), presents specific geological, morphotectonic and climatic characteristics which influence the hydrogeological regime. The vadose zone has particular features that contribute to control both the quantity and the quality of the groundwater resources. The regional characterisation of this zone was carried out in terms of the structure, the soil, including the broad physical, chemical and mineralogical features and the soil hydraulics. The study included field work focused on geological and pedological features, soil permeability field tests, laboratory tests (including soil water retention at different pressure heads and clay mineralogy) and mathematical modelling. Water retention data were used to derive the parameters of van Genuchten's water retention curve. Unsaturated hydraulic conductivity was estimated using the Gardner mathematical model.

1 INTRODUCTION

Mountain areas usually support water resources of both of good quality and of significant social and economic importance. The seasonality and spatial variability of groundwater signatures as well as the complex role of soils, geomorphology, geology, climate, land cover and human activities in the hydrology of mountain areas is difficult to model, even when the relevant data are available. Understanding the role of the vadose zone is essential to assess hydrogeological systems and the respective groundwater resources accurately (e.g. Dingman,

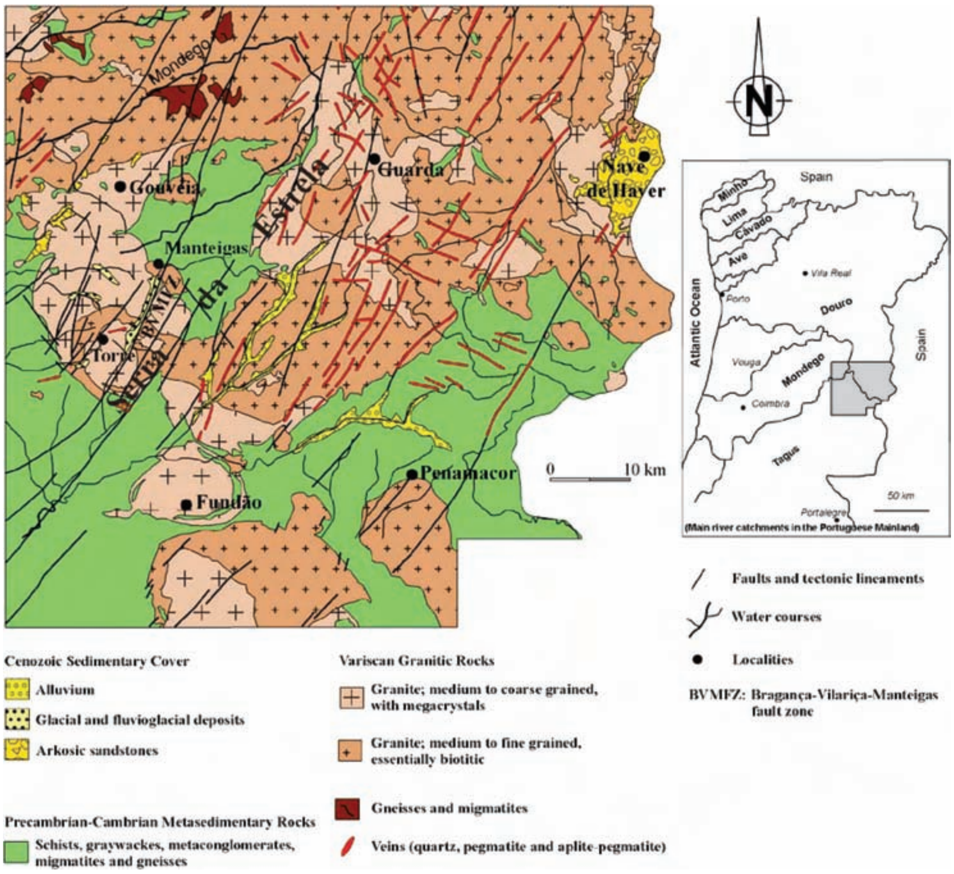


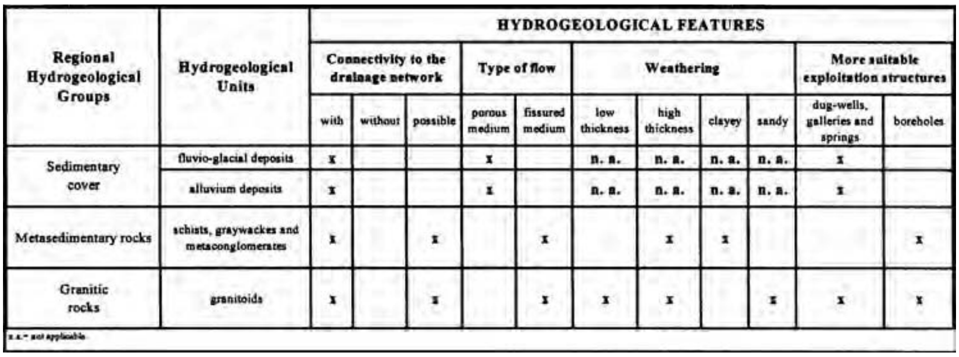
Figure 1. Geological framework of Serra da Estrela region (adapted from Geological Map of Portugal, 1/50,0000, 5th Edition; Oliveira et al. 1992).

1994; NAP, 2001). Consideration should be given to soil formation factors such as parent material, topography, climate, organisms and human action, as these may also control the volume of infiltration and groundwater recharge.

The study area is the Manteigas – Nave de Santo António – Torre sector, located in the *Serra da Estrela* mountain (Central Portugal), that is, the drainage basin of the River Zêzere upstream of Manteigas village (Figure 1). The regional aquifer system presents specific geological, morphotectonical and climatic characteristics, which contribute to control the local hydrogeological regime. Therefore, the corresponding vadose zone has particular features that control both the quantity and the quality of the groundwater resources.

The study was performed between 2003 and 2005 within the scope of the multidisciplinary hydrogeologic *R&D Project "HIMOCATCH"* (Espinha Marques et al., 2005). This regional-scale vadose zone characterisation was supported by geological, pedological and hydrogeomorphological analyses and focused on the physical, chemical and mineralogical features of the soil, vadose zone structure and the soil hydraulics. Soil hydraulic and mineralogical features in this sector result from the particular way in which the pedogenetic factors act in a mountain environment.

Table 1. Main hydrogeological features of the Serra da Estrela mountain region.



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	fluvio-glacial deposits	x			x		n. a.	n. a.	n. a.	n. a.	x	
	alluvium deposits	x			x		n. a.	n. a.	n. a.	n. a.	x	
Metasedimentary rocks	schists, graywackes and metaconglomerates	x		x		x		x	x			x
Granitic rocks	granitoids	x		x		x	x	x		x	x	x

n.a. = not applicable

The tasks carried out included fieldwork focused on geological and pedological features, field and laboratory tests and mathematical modelling. Soil samples were collected at selected sites. Soil permeability field tests were performed. Laboratory tests were conducted in order to determine, among other aspects, water retention at different pressure heads and clay mineralogy. Unsaturated hydraulic conductivity was estimated with the Gardner mathematical model. Water retention data were used to derive the parameters of the van Genuchten water retention curve. With the resulting characteristic curves it was possible to compare the Serra da Estrela soil with soils from other locations. Additionally, the effect of texture and organic matter on soil water retention was evaluated.

2 HYDROGEOLOGIC FRAMEWORK

The Serra da Estrela region is part of the Central-Iberian Zone of the Iberian Massif (Ribeiro et al., 1990). The main lithotypes found in the region are (Figure 1): i) Variscan granitic rocks; ii) Precambrian-Cambrian metasedimentary rocks; iii) alluvium and Quaternary glacial deposits. The largest regional tectonic structure is the NNE-SSW Bragança-Vilariça-Manteigas fault zone (BVMFZ). According to Ribeiro et al. (1990), the origin of the Serra da Estrela Mountain is connected to an uplift process related to the reactivation of the BVMFZ megastructure during Cenozoic times, by the Alpine compressive tectonics, together with the reactivation of major ENE-WSW trending reverse faults (such as the Seia-Lousã fault).

An important issue related to the infiltration and aquifer recharge in the Serra da Estrela region is the identification of areas of prevailing fractured or porous media (Espinha Marques et al., 2005). In particular, porous media occur in alluvium and Quaternary glacial deposits as well as in the weathered and brittle/sheared granites and metasedimentary rocks. Porous media usually occur at shallow depths (typically less than 50 m). On the other hand, fractured media occur in weakly weathered rocks. Such media may be present very close to the surface (especially in areas where granite outcrops dominate, with thin or absent sedimentary cover) or below the shallow porous materials. The regional hydrogeological units correspond closely to the major geological features (Table 1): i) sedimentary cover, including alluvium and Quaternary glacial deposits; ii) metasedimentary rocks, including schists and graywackes; and iii) granitic rocks.

Serra da Estrela is the highest mountain in the Portuguese mainland (with an altitude reaching 1993 m a.s.l.) and is part of the Cordilheira Central, an ENE-WSW mountain range that crosses the Iberian Peninsula. This region shows distinctive climatic and geomorphologic characteristics that play an important role in the local water cycle. The river Zêzere drainage basin upstream of Manteigas has an area of around 28 km^2 with an altitude ranging from 875 m a.s.l., at the streamflow gauge measurement weir of Manteigas, to 1993 m a.s.l., at the Torre summit (Figure 2). The relief of the study area consists mainly of two major plateaus, separated by the NNE-SSW valley of the Zêzere River (Vieira 2004): the western Torre–Penhas Douradas plateau (1450–1993 m a.s.l.) and the eastern Alto da Pedrice–Curral do Vento plateau (1450–1760 m a.s.l.). Late Pleistocene glacial landforms and deposits are distinctive features of the upper Zêzere catchment, since the majority of the plateau area was glaciated during the Last Glacial Maximum (e.g. Daveau et al., 1997; Vieira, 2004).

Espinha Marques et al. (2005) proposed 9 hydrogeomorphologic units, based on the spatial distribution of lithological, geomorphological and climatic features (Figure 2): (i) the eastern plateau; ii) Zêzere valley eastern slopes; iii) Lower Zêzere valley floor; iv) Nave de Santo António col; v) upper Zêzere valley floor; vi) Zêzere valley western slopes; vii) Cântaros slopes; viii) lower western plateau; ix) upper western plateau.

The Serra da Estrela climate has a Mediterranean climate, i.e., dry and warm summers, and the wet season extends from October to May, and the mean annual precipitation is about 2500 mm on the Torre summit and more than 2000 mm on the plateaux (Daveau et al., 1997; Vieira and Mora, 1998). Precipitation seems to be controlled mainly by the slope orientation and the altitude. According to Vieira and Mora (1998), the warmest month is July and the coldest is January. Mean annual air temperatures are below 7°C in most of the plateaux area and, in the Torre vicinity, they may be as low as 4°C. The spatial and temporal irregularity of snow-related phenomena has been analysed in earlier studies (e.g., Mora and Vieira, 2004).

3 VADOSE ZONE CHARACTERISATION

Since soils contribute to control both the volume of recharge and the water chemistry in an aquifer system, they were the main target of the regional-scale vadose zone study at Serra da Estrela. Soil features greatly influence the volume of water that infiltrates during a precipitation event, so controlling aquifer recharge as well as the short-term stream response.

The most important factors usually identified that affect the balance between infiltration and overland flow are the amount and temporal distribution of precipitation (or irrigation), the physical and chemical soil features (e.g. texture, organic-matter content, saturated hydraulic conductivity at the surface, clay mineralogy, presence of water-repellent substances), previous soil water saturation, surface slope and roughness, land cover, land use and amount of evapotranspiration (e.g., Dingman, 1994). The vadose zone study included several field studies carried out in 2004 and 2005. During these studies, soil samples were collected for physical, chemical and mineralogical characterisation (Figure 2). Detailed vadose zone studies were carried out at specific sites. Table 2 describes each study site in terms of parent material, relief, land cover and dominant soil profile.

The parent material of all studied soils is granite or granite derived glacial deposits. These soils are coarse-textured, as shown in Figure 3, obtained from analyses of A and C horizon samples. In the A horizon, particles coarser than 2 mm (mainly fine and medium sized pebbles) correspond to an average value of 34% by weight (with a standard deviation of 12%). Other A horizon features (bulk density and total porosity, determined on soil cores, and pH and organic matter content, determined in the fine earth fraction) are presented in Table 3. The soil cores

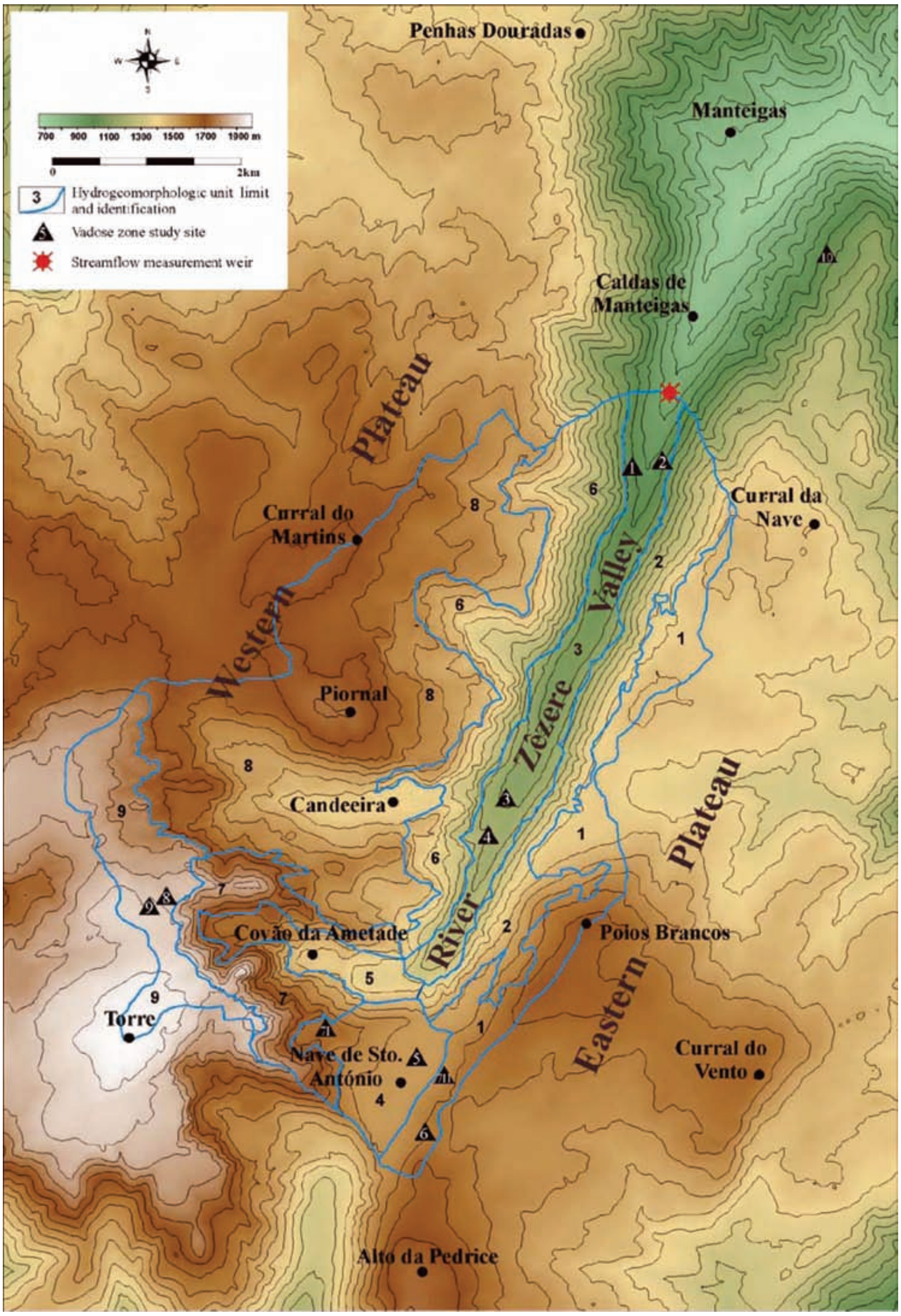


Figure 2. Hypsometric features of the river Zêzere drainage basin upstream of Manteigas; vadose zone study sites; hydrogeomorphologic units: Eastern plateau (1); Zêzere valley eastern slopes (2); Lower Zêzere valley floor (3); Nave de Santo António col (4); Upper Zêzere valley floor (5); Zêzere valley western slopes(6); Cântaros slopes (7); Lower western plateau (8); Upper western plateau (9).

Table 2. Main features of the vadose zone study sites.

Site	Parent material	Topography/Geoform	Land cover	Prevailing soil profile
1	Glacial deposit	Base of slope	Maritime pine woodland	A-C
2	Glacial deposit	Base of slope	*Genista florida* and *Cytisus* sp.pl. scrubland	A-C
3	Glacial deposit	Valley floor	Meso-hygrophilous grassland	A-C
4	Glacial deposit	Base of slope	Meso-xerophilous grassland	A-C
5	Glacial deposit	Col	*Nardus stricta* grassland	A-C
6	Granite	Base of slope	Heathland	A-C or A-C-R
7 (I, II)	Glacial deposit	Base of slope	Heathland	A-C
8	Granite	Plateau	*Nardus stricta* grassland	A-R
9	Granite	Plateau	Common juniper shrubland	A-R
10	Granite	Slope	*Quercus pyrenaica* forest	A-B-C-R

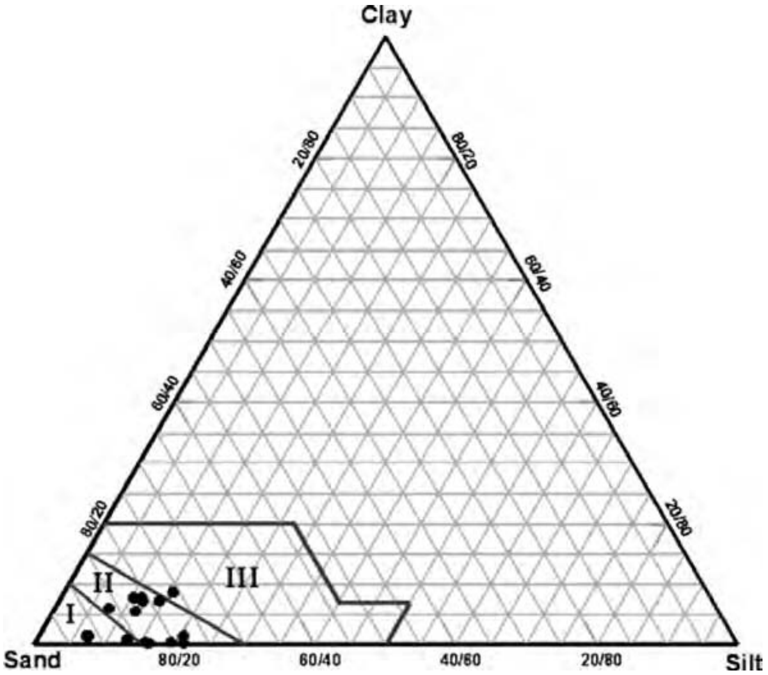


Figure 3. Soil texture classification; texture classes: sand (I), loamy sand (II) and sandy loam (III).

were obtained with metal cylinders following the recommendations of Topp et al. (1993) in order to get representative samples and to minimize soil disturbance during collection and transportation. Additionally, Table 3 includes the volumetric water content (θ) measured in the relevant soil cores through the pressure-plate method (e.g., Topp et al., 1993) in A horizon samples at different pressure heads (h): −50 cm, −100 cm, −500 cm and −15850 cm. The soil cores were saturated inside their metal cylinders prior to insertion into the pressure plate device, with precautions taken to avoid air entrapment. Thus, the resulting values of volumetric water content at saturation were very close to the total porosity.

Table 3. Main features of the A horizon.

Site	Bulk density ($g \cdot cm^{-3}$)	Total porosity (%)	pH	Organic matter ($g \cdot kg_{-1}$)	θ (% of volume) at different h values			
					−50 cm	−100 cm	−500 cm	−15850 cm
1	1.25	44.7	4.6	71.7	23.3	19.9	14.3	12.3
2	1.26	49.6	4.6	57.4	29.3	23.8	15.7	12.2
3	1.16	52.7	4.8	71.6	34.4	30.8	22.4	18.6
4	1.21	42.7	4.4	48.8	23.5	19.5	14.3	11.5
5	0.94	49.7	4.1	133.1	42.0	33.7	25.5	22.2
6	1.07	45.2	4.7	103.8	29.3	23.8	17.8	16.4
7I	0.88	51.9	4.1	187.5	44.7	37.2	26.8	25.2
7II	1.09	53.4	4.3	71.1	35.7	28.5	21.5	19.1
8	0.68	62.2	4.3	240.5	57.3	50.9	40.8	38.1
9	0.88	55.6	4.3	188.4	46.1	37.7	28.7	26.9
10	0.96	48.4	4.8	84.1	31.2	26.0	18.8	15.8
Average	1.03	50.6	4.5	114.3	36.1	30.2	22.4	19.8

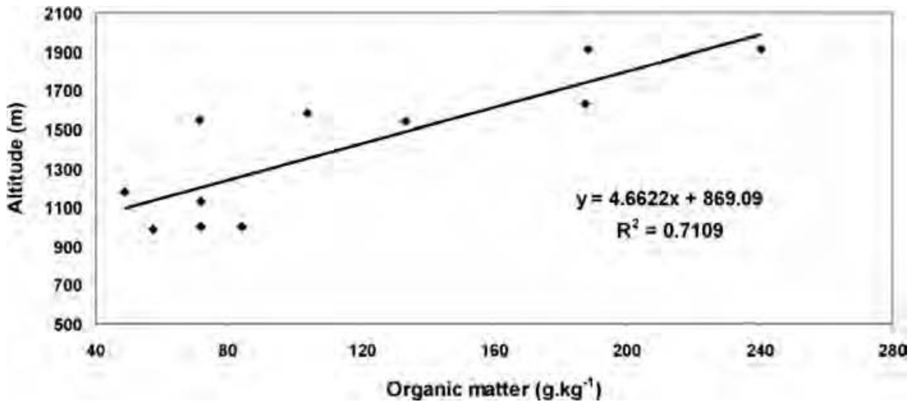


Figure 4. Relation between soil organic matter and altitude.

The spatial distribution of soil organic matter in the A horizon depends principally on altitude (Figure 4), mainly due to a climatic effect well known in Northern and Central Portugal (e.g., Agroconsultores and Geometral, 2004; Pereira et al., 2006). Higher soil organic matter contents are usually found in upper regions characterised by minimum mean yearly air temperature and maximum precipitation. In fact, soils from the Torre area (Figure 2) present the highest measured organic-matter contents ($240.5\,g \cdot kg^{-1}$), whereas soils from lower areas have measured values ranging from 48.8 to $84.1\,g \cdot kg^{-1}$. A significant effect of organic matter versus bulk density and total porosity (with important implications for soil hydraulic properties) was observed: more organic soils tend to have lower bulk density and higher total porosity. However, this is a regional trend which does not exclude the influence of other factors (such as land cover, land use or geomorphology among others), especially relevant on a local scale.

Mineralogical analyses of the fine soil fractions (silt and clay) reveal a clearly detrital mineralogy, rich in phyllosilicates (mainly micas), quartz, plagioclases and K-feldspars, with, as accessory minerals, siderite, opal C/CT, anhydrite, hematite, ilmenite, anatase, zeolites (mainly heulandite-clinoptilolite), gibbsite, rozenite and jarosites. Samples related to granites show higher amounts of phyllosilicates.

As a general rule, illite is the predominant clay mineral, but samples related to granites show a trend toward a relative decrease of illite contents whereas kaolinite and, in some samples, vermiculite-Al and/or smectite, increase. Significant amounts of vermiculite-Al occur at sites 1, 3, 4 and 10 (the sampling sites situated at lower altitudes), particularly in their A horizons. On the other hand, the expansive clay minerals (smectite and irregular mixed-layers illite-smectite) show a relative increase at sites 2, 6, 8, 9 and 10 (essentially, soils developed on granite).

According to the soil map of the Serra da Estrela region (Agroconsultores and Geometral, 2004) the following pedologic units occur in this sector: (i) Humic, Leptic and Skeletic Umbrisols; (ii) Lithic and Umbric Leptosols; (iii) Umbric Fluvissols; (iv) Rock outcrops.

Field observations produced further information concerning the pedologic units, their spatial distribution according to the hydrogeomorphologic framework and their hydrologic classification by means of the Hydrologic Soil Groups system (from low runoff potential soils, group A, to high runoff potential soils, group D) – (e.g. USSCS 1964, Langan and Lammers, 1991; Boulding, 1993).

Some of the most distinctive features of the vadose zone in this sector of Serra da Estrela are the wide distribution of: (i) granitic rock outcrops and (ii) an umbric A horizon – and consequently, Umbrisols and Umbric Leptosols — thus reflecting the high organic-matter content in the upper part of the soil profile. On the plateau and slopes of hydrogeomorphologic units 1 and 2 (see Figure 2) similar sets of pedologic units occur: Leptic Umbrisols dominate (especially in unit 2); rock outcrops and Umbric Leptosols are secondary. Skeletic Umbrisols are dominant in units 3 (valley floor) and 4 (col); Humic Umbrisols and Umbric Fluvisols are subdominant. In unit 5, rock outcrops prevail, whereas Umbric Leptosols and Fluvisols are subdominant; minor occurrences of Leptic Umbrisols were observed. Rock outcrops are also dominant in the remaining units (6 to 9) but in the upper part of unit 6 slopes, Lithic and Umbric Leptosols are subdominant, while in the lower part of the slopes these soils are replaced by Skeletic and Leptic Umbrisols. In the rocky slopes of unit 7, there are minor occurrences of Umbric and Lithic Leptosols. In the plateau area of units 8 and 9 Lithic and Umbric Leptosols are subdominant whilst smaller areas of Leptic Umbrisols were found in unit 8.

Four types of vadose zone structures were identified in the region:

- Type (i) Composed of a single granite layer with very thin or absent soil cover; present in granitic outcrop areas of plateaus and slopes. Water circulation in fractured medium. Included in soil hydrology group D.
- Type (ii) Composed of a soil layer typically less than 0.5 m thick overlying a continuous and hard granitic layer; described at sites 6, 8 and 9 (see Table 2); present on plateaus, especially above 1600 m a.s.l., and slopes. Coexistence of porous and fractured media. Corresponding to Lithic and Umbric Leptosols (both included in soil hydrology group D).
- Type (iii) Composed of a soil layer frequently between 0.5 and 1.0 m thick overlying a weathered granite layer and/or a slope deposit; described at sites 6 and 10; it is present on lower altitude slopes and plateaux (where chemical weathering processes are more active) or along tectonised zones. Both porous and fractured media. Corresponding essentially to Leptic Umbrisols with C horizon composed of weathered granite and/or a slope deposit. These soils are included in hydrology group C.

Figure 5. The constant-head well permeameter: general view (a), well head scale (b), water reservoir (c), tripod (d) and soil auger set (e).

– Type (iv) composed of a soil layer frequently over 1.0 m thick overlying a glacial deposit; described at sites 1 to 5 and 7; present at the base of a slope, col and valley floor areas; porous medium. Prevailing Skeletic and Humic Umbrisols (A, B or C hydrology groups) and subdominant Umbric Fluvisols (C or D hydrology groups).

The importance of *in situ* evaluations of saturated hydraulic conductivity ($\mathbf{K_s}$) for accurate determination of water movement in the field related to infiltration and runoff is a well established fact (Reynolds, 1993). K_s measured in the vadose zone is usually referred to as *field-saturated hydraulic conductivity* ($\mathbf{K_{fs}}$). As complete saturation is not achieved in such field tests, K_{fs} can be a factor of 2 (or more) below K_s (Bouwer, 1978; Reynolds and Elrick, 1987).

The soil permeability study consisted of a set of 40 field tests carried out at sites 1, 2, 3, 5, 6, 8, 9 and 10 (Figure 5) by means of the constant-head well permeameter also known as the *Guelph permeameter* method (e.g. Reynolds and Elrick, 2002). In this study, a borehole 15 m deep and 6 cm in diameter (manually excavated with an auger) was used together with two successively ponded heads (5 and 10 cm). All tests refer to A horizon. The following expressions were used to calculate K_{fs}:

$$K_{fs} = (G_2.Q_2) - (G_1.Q_1)$$

where

$$G_2 = \frac{H_1.C_2}{\pi\left[2H_1.H_2\left(H_2 - H_1\right) + r^2\left(H_1.C_2 - H_2.C_1\right)\right]}$$

and

$$G_1 = G_2\ (H_2.C_1)/\ (H_1.C_2);\ Q_1 = AR_1;\ Q_2 = AR_2$$

$\mathbf{H_1}$ and $\mathbf{H_2}$ (L) are the two successively ponded heads ($H_1 < H_2$); **r** is the well radius (L); $\mathbf{C_1}$ and $\mathbf{C_2}$ are shape factors corresponding to $f(H_1/r)$ and $f(H_2/r)$, respectively (see Reynolds and Elrick, 2002); $\mathbf{R_1}$ and $\mathbf{R_2}$ are the steady rates of fall of the water in the permeameter reservoir (LT^{-1}) corresponding to H_1 and H_2, respectively; **A** is the reservoir cross-sectional area (L^2).

The measured K_{fs} values are presented in Table 4, each value representing the average of five field tests. In all cases the permeability is high (assuming $K_s = 2\,K_{fs}$) according to the SSDS (1993) classification.

An estimate of the unsaturated hydraulic conductivity (K) was also obtained using the empirical function of K(h) by Gardner (1958):

$$K(h) = K_{fs}\ \exp[a(h\text{-}h_e)]\ \text{if}\ 0 < a < +\infty\ \text{and}\ h < h_e \leqslant 0$$

$$K(h) = K_{fs}\ \text{if}\ h \geqslant h_e$$

h is the pressure head (L); **a** (L^{-1}) is a slope parameter that depends mainly on soil texture and structure; $\mathbf{h_e}$ is an entry pressure head which represents the air entry pressure head for drainage from field saturation and the water entry pressure head for wetting up to field saturation. In most natural soils $\mathbf{h_e} \approx \mathbf{0}$ and $\mathbf{a} \approx \mathbf{a}^*$ (L^{-1}) (Reynolds et al., 2002). **a*** represents the ratio of gravity to capillary forces during infiltration or drainage. Figure 6 illustrates the unsaturated hydraulic conductivity as a function of pressure head assuming the average K_{fs} value for Serra da Estrela soils (7.8544 cm/h) and the value of **a*** indicated by Elrick et al. (1989) for coarse soils (0.36 cm^{-1}).

The hydraulic description of the vadose zone also included the determination of soil characteristic curves. For this purpose, the analytical model proposed by van Genuchten (1980) was fitted to the measured water retention values (see table 3) by means of the RETC v6.0 code (van Genuchten et al., 1991; Yates et al., 1992) available at *http://www.ars.usda.gov/* internet site.

Table 4. Measured values of field saturated hydraulic conductivity.

Site	Measured K_{fs} (cm/h)	
	Average	Standard deviation
1	7.7864	5.5269
2	4.7399	1.5484
3	4.1947	1.8637
5	3.3135	2.3662
6	12.7172	4.0201
8	4.6740	1.8532
9	12.8208	7.9673
10	12.5890	3.6269
All field tests	7.8544	5.4920

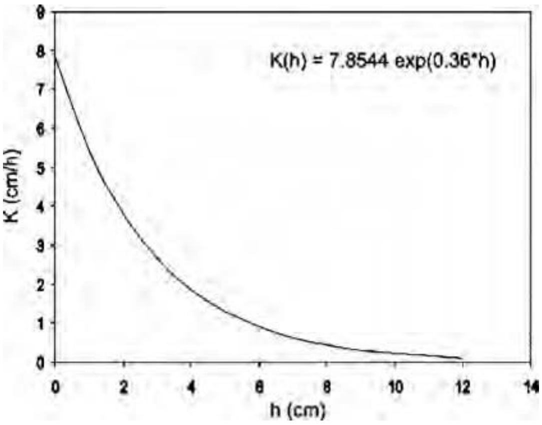


Figure 6. Unsaturated hydraulic conductivity (K) as a function of pressure head (h) for Serra da Estrela soils.

Van Genuchten (1980) defined the relationship between pressure head (**h**) and the soil volumetric water content (θ) by the expression:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m}$$

where

$$n = \frac{1}{1 - m} \quad \text{and} \quad \alpha = \frac{1}{h_b}\left(2^{1/m} - 1\right)^{1-m}$$

Table 5. Estimated values of the van Genuchten soil parameters.

Site	$\theta_r^{(1)}$ (% vol.)	$\theta_s^{(2)}$(%vol.)	$n^{(1)}$	$\alpha^{(1)}$	R^2
1	11.8	44.7	1.6253	0.1017	0.996
2	11.6	49.6	1.6371	0.0604	0.999
3	17.5	52.7	1.5129	0.0739	0.992
4	11.1	42.7	1.5950	0.0901	0.999
5	22.5	49.7	2.0139	0.0198	0.996
6	16.3	45.2	1.9233	0.0423	0.999
7I	25.0	51.9	2.2104	0.0170	0.999
7II	19.0	53.4	1.9001	0.0394	0.999
8	38.0	62.2	2.0875	0.0148	0.999
9	26.9	55.6	2.1947	0.0205	0.999
10	15.4	48.4	1.6710	0.0523	0.999
Average studied soils	19.6	50.6	1.8519	0.0484	–
Average coarse-textured soils$^{(3)}$	5.6	41.7	2.2833	0.1147	–

(1) estimated; (2) assumed equal to total porosity according to Fetter (1999);
(3) after Carsel and Parrish (1988).

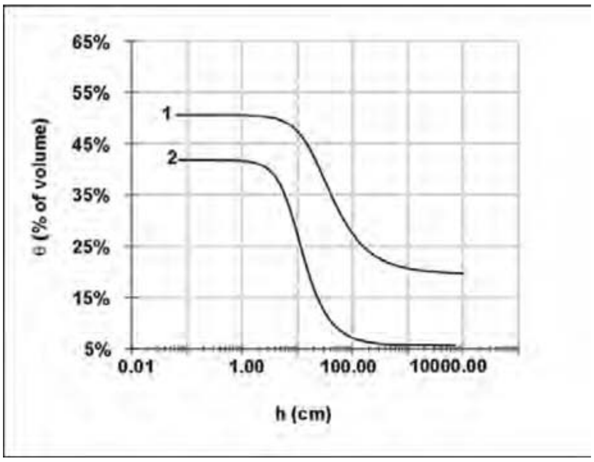


Figure 7. Water-retention curves: Serra da Estrela soils (1) and average coarse-textured soils (2).

θ and h are as defined earlier; $\boldsymbol{\theta}_s$ is the water content at saturation; $\boldsymbol{\theta}_r$ is the residual water content; $\mathbf{h_b}$ is the bubbling pressure head; **m** is an empirical constant affecting the shape of the retention curve.

Table 5 presents the estimates of van Genuchten parameter values resulting from the application of RETC code to observed volumetric water contents. The best results were obtained considering θ_s values equal to the total porosity, assuming the procedure proposed by Fetter (1999); R^2 values stand for the regression of observed versus fitted θ values. These results are compared to average values of coarse-textured soils obtained through experimental means by Carsel and Parrish (1988).

Figure 7 illustrates the contrast between the hydraulic behaviour of Serra da Estrela soils and the reference soils of Carsel and Parrish (1988). It is noticeable that for analogous h values

Serra da Estrela soils present higher θ values. This effect becomes more apparent in the curve region corresponding to greater suctions (more negative pressure heads), that is, where most water is retained in micropores. Since these soils have relatively high organic-matter and low clay contents (see Table 3 and Figure 3) the observed trend should be explained by the former feature. The correlation coefficients (R) of organic matter versus water retention at -50 cm and -15850 cm (0.92 and 0.94, respectively) support this idea.

4 CONCLUDING REMARKS

Given that the role of the vadose zone is essential to understanding the genesis and evolution of groundwater resources, a multidisciplinary approach supported by geological, pedological and hydrogeomorphological analyses was used , providing important information to achieve a regional scale characterization of the vadose zone in the hydrogeological system of the Manteigas- Nave de Santo António-Torre sector. This description focused on the broad physical, chemical and mineralogical soil features, vadose zone structure, and soil hydraulics.

Although coarse textures and low pH tend to be common soil features in Serra da Estrela, organic-matter content and, therefore, bulk density and total porosity, are related to altitude due to the climatic effect. The mineralogical soil study focused on clay mineralogy. In fact, fine- fraction soil mineralogy is closely related to a detrital origin (with absolute predominance of quartz, mica/illite and feldspars). Nevertheless, some distinctive features are evident, particularly: samples related to granites which show relatively higher amounts of phyllosilicates (but a decrease in illite whereas kaolinite increases).

A distinctive feature of the vadose zone in this sector of Serra da Estrela is the wide distribution of granitic rock outcrops and an umbric A horizon and, consequently, Umbrisols and Umbric Leptosols, thus reflecting the high organic-matter content in the upper part of the soil profile.

Four types of vadose zone structures were identified, with a spatial distribution closely controlled by geology and hydrogeomorphology. High runoff potential soil hydrology groups (C and D) are dominant in spite of the high permeability of the A horizon, measured by means of the constant-head well permeameter. Unsaturated hydraulic conductivity was estimated with the Gardner equation.

The parameters of van Genuchten water-retention curve were derived from water-retention data in A horizon samples. According to the resulting characteristic curves, it is noticeable that for analogous pressure head values Serra da Estrela soils present higher water-retention values than the average coarse-textured soils, especially in the curve region corresponding to greater suction (in which case water is mainly retained in micropores). This contrast is explained by the high organic- matter content of the studied soils.

ACKNOWLEDGMENTS

This study was performed within the scope of the HIMOCATCH *R&D* Project granted by the Portuguese Foundation for Science and Technology (FCT) and FEDER EU funds, contract POCTI/CTA/44235/02. Constructive comments by the two anonymous reviewers greatly improved the manuscript.

REFERENCES

Agroconsultores, Geometral (2004) Elaboração da Carta de Solos e de Aptidão das Terras da Zona Interior Centro (Making of the Soil Map and Land Suitability of Zona Interior Centro). Instituto de Desenvolvimento Rural e Hidráulica, Lisbon, 313pp

Boulding JR (1993) Subsurface characterization and monitoring techniques. In: The vadose zone, field screening and analytical methods. EPA/625/R-93/003

Bouwer H (1978) Groundwater Hydrology. McGraw-Hill, Inc, New York, 480 pp

Carsel FF, Parrish RS (1988) Developing joint probability distributions of soil water retention characteristics. Water Resources Research, 24,5, 755–769

Daveau S, Ferreira AB, Ferreira N, Vieira G (1997) Novas observações sobre a glaciação da Serra da Estrela (New observations on the Serra da Estrela glaciation). Estudos do Quaternário 1:41–51

Dingman SL (1994) Physical hydrology. Prentice Hall, New Jersey, 575 pp

Elrick DE, Reynolds WD and Tan KA (1989) Hydraulic conductivity measurements in the unsaturated zone using improved well analyses. Ground Water Monit. Rev., 9, 3, 184–193

Espinha Marques J, Marques JM, Chaminé HI, Afonso MJ, Carreira PM, Fonseca PE, Cabral J, Monteiro Santos FA, Vieira GT, Mora C, Gomes A, Teixeira J, Samper J, Pisani BJ, Aguiar C, Gonçalves JA, Almeida PG, Cavaleiro V, Carvalho JM, Sodré Borges F, Aires-Barros L, Rocha FT (2005) Hydrogeological study of a high mountain area (Serra da Estrela, Central Portugal): a multidisciplinary approach. Cadernos Lab Xeol Laxe, 30, 145–166

Fetter CW (1999) Contaminant hydrogeology. Prentice-Hall, Inc, New Jersey 500 pp

Gardner WR (1958) Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci., 85, 228–232.

Langan LN, Lammers DA (1991) Definitive criteria for hydrologic soil groups. Soil Survey Horizons, 32, 3, 69–77

Mora C, Vieira GT (2004) Balance radiactivo de los altiplanos de la Sierra de Estrella (Portugal) en una mañana de invierno. Metodología y primeros resultados (Radiation balance of the plateaus of Sierra de Estrella (Portugal) in a winter morning. Methodology and first results). Bol. R. Soc. Esp. Hist. Nat. (Sec Geol), 99, 1–4, 37–45

NAP – National Academy Press (2001) Conceptual models of flow and transport in the fractured vadose zone. Washington DC, 374 pp

Oliveira JT, Pereira E, Ramalho M, Antunes MT, Monteiro JH ,Coords (1992) Carta Geológica de Portugal a escala 1/500 000 (Geological Map of Portugal, scale 1/500 000). 5th Edition. Portuguese Geological Survey, Lisbon.

Pereira SP, Correia AV, Correia AC, Ferreira MT, Onofre N, Freitas H, Godinho F (2006) Florestas e Biodiversidade (Forests and Biodiversity): In: Santos FD, Miranda P (eds) Alterações climáticas em Portugal; cenários, impactos e medidas de remediação, Projecto SIAM II (Climate change in Portugal; scenarios, impacts and adaptation measures, SIAM II Project), Gradiva, Lisbon, pp 305–343

Reynolds WD (1993) Saturated hydraulic conductivity: field measurement: In: Carter MR (ed) Soil sampling and methods of analysis, Lewis Publ, Boca Raton, pp 599–613

Reynolds WD, Elrick DE (1987). A laboratory and numerical assessment of the Guelph permeameter method. Soil Sci., 144, 282–299

Reynolds WD, Elrick DE (2002) Constant head well permeameter (vadose zone). In: Dane JH, Clarke Topp G (ed) Methods of soil analysis, Soil Science Society of America, Inc., part 4, Physical methods, 844–858.

Reynolds WD, Elrick DE, Youngs EG, Amoozegar A, Booltink HWG and Bouma J (2002) Saturated and field-saturated water flow parameters: In: Dane JH, Topp GC (eds) Methods of soil analysis, part 4, Physical methods. Soil Science Society of America, Inc, Madison, pp 797–878

Ribeiro A, Kullberg MC, Kullberg JC, Manuppela G, Phipps S (1990) A review of Alpine tectonics in Portugal: Foreland detachment in basement and cover rocks, Tectonophisics, 184, 357–366

SSDS, Soil Survey Division Staff (1993) Examination and description of soils: In: Soil Survey Manual. Agricultural Handbook 18, chapter 3

Topp GC, Galganov YT, Ball BC, Carter MR (1993) Soil water desorption curves: In: Carter MR (ed) Soil sampling and methods of analysis, Lewis Publ, Boca raton, pp 569–579

USSCS, U. S. Soil Conservation Service (1964) Hydrology: In: SCS National Engineering Handbook, Section 4

Van Genuchten MT (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898

Van Genuchten MT, Leij FJ, Yates SR (1991) The RETC code for quantifying the hydraulic functions of unsaturated soils. U S Environmental Protection Agency 85 pp

Vieira GT (2004) Geomorfologia dos planaltos e altos vales da Serra da Estrela: ambientes frios do Plistocénico Superior e dinâmica actual (Geomorphology of the plateaus and high valleys of Serra da Estrela: cold environments from Late Pleistocene and present dynamics). Unpublished PhD Thesis, Department of Geography, University of Lisbon, 724pp

Vieira GT, Mora C (1998) General characteristics of the climate of the Serra da Estrela: In Vieira GT (ed), Glacial and Periglacial Geomorphology of the Serra da Estrela, Guidebook for the field-trip, IGU Commission on Climate Change and Periglacial Environments, CEG and Department of Geography, University of Lisbon pp 26–36

Yates SR, van Genuchten MT, Warrick AW, Leij FJ (1992) Analysis of measured, predicted and estimated hydraulic conductivity using the RETC computer program. Soil Sci. Soc. Am. J., 56, 347–354