A PRELIMINARY HYDROGEOLOGIC CONCEPTUAL MODEL OF THE MANTEIGAS-NAVE DE SANTO ANTÓNIO-TORRE SECTOR (SERRA DA ESTRELA NATURAL PARK, CENTRAL PORTUGAL)

Jorge Espinha Marques [1]©, José M. Marques [2], Helder I. Chaminé [3], Paula M. Carreira [5], Paulo E. Fonseca [6], Javier Samper [7], B. Pisani [7], D. Alvares [7], Gonçalo T. Vieira [8], Carla Mora [8], José Teixeira [4], Alberto Gomes [9], José Martins Carvalho [3], Frederico S. Borges [1], Fernando T. Rocha [4]

[1] Dep. de Geologia (CGUP), Faculdade de Ciências da Universidade do Porto, Praça de Gomes Teixeira, 4099-002 Porto, Portugal. (© jespinha@fc.up.pt); [2] Dep. de Engenharia de Minas e Georrecursos, Instituto Superior Técnico (IST), Lisboa, Portugal; [3] Dep. de Engenharia Geotécnica, Instituto Superior de Engenharia do Porto (ISEP), Portugal; [4] Centro de Minerais Industriais e Argilas, Dep. de Geociências, Universidade de Aveiro, Portugal; [5] Dep. de Química, Instituto Tecnológico e Nuclear (ITN), Sacavém, Portugal; [6] Dep. de Geologia, Faculdade de Ciências da Universidade de Lisboa (LATTEX), Portugal; [7] Escuela Tecnica Superior de Ingenieros de Caminos, Canales y Puertos, Universidad de La Coruña, Spain; [8] Centro de Estudos Geográficos, Universidade de Lisboa, Portugal; [9] Dep. de Geografia, Universidade do Porto, Portugal.

ABSTRACT

This work is strongly connected with one of the most crucial water research issues at the turn of the millennium "High Mountain Areas Hydrology" (UNESCO IHP-VI Programme). Special emphasis is dedicated to high mountains and their role and impact on surface water/groundwater interaction at Serra da Estrela region - Central Portugal, in order propose a preliminary hydrogeologic conceptual model of the Manteigas - Nave de Santo António - Torre sector, contributing to i) increase knowledge on recharge and discharge processes in this high mountain area and ii) assess the role of snowmelt as a source of groundwater resources, with the aid of coupled isotopic and geochemical techniques. The isotopic signatures of Caldas de Manteigas thermomineral waters combined with the i) morpho-structural data and ii) isotopic composition of shallow groundwater and precipitation samples, made it possible to identify possible recharge areas, which should be located at altitude sites above 1500 m a.s.l.. The recharge altitudes are similar to those of Nave de Santo António area which is directly located on the Bragança-Vilariça-Manteigas fault zone. This tectonic structure should play an important role in groundwater recharge and circulation towards the discharge zone at the Spas.

KEYWORDS

Groundwater, mountain hydrology, isotope hydrology, hydrogeochemistry, hydrological modelling.

INTRODUCTION

This paper is strongly related to one of the central water research issues of this millennium: "High Mountain Areas Hydrology" (see UNESCO IHP-VI Programme: http://www.unesco.org). Special emphasis is dedicated to thermal waters and non-thermal groundwaters issuing at the Manteigas–Nave de Santo António–Torre sector, situated in Serra da Estrela High Mountain area (Central Portugal). The selected study area is located in the vicinity of a regional morphostructure — Bragança–Vilariça–Manteigas fault zone (BVMFZ) — on the sector that intersects the central massif of Serra da Estrela.

The research area corresponds to the river Zêzere drainage basin upstream of Manteigas village which presents specific geotectonic, geomorphologic and climatic characteristics controlling local groundwaters recharge and circulation. Besides the presence of important thermal water resources (allowing the installation of the Caldas de Manteigas Spa), this area is characterised by the existence of other strategic groundwater resources (e.g., high quality drinking water for bottling and domestic use at Manteigas village) which seem to be also strongly dependent on geomorphology (recharge areas) and geotectonics (active faults responsible for groundwater circulation).

The geological, morphostructural, hydrogeochemical and climatic information were used to outline a preliminary conceptual model comprising the main components of the studied hydrogeologic system, namely: i) altitudes of recharge areas, ii) groundwater circulation zones and iii) discharge areas. Such a model provides an essential instrument to the decision making process related to the water and land use management at this region.

HYDROGEOLOGICAL SETTING

The Serra da Estrela region (fig. 1) is part of the Central-Iberian Zone of the Iberian Massif (Ribeiro et al., 1990). The geological conditions outline some of the major hydrogeologic features and processes, such as infiltration, aquifer recharge, type of flow medium (porous vs. fractured), type of groundwater flowpaths, or hydrogeochemistry.

The main lithotypes occurring in the region are (fig. 2a): i) Variscan granitic rocks; ii) Precambrian-Cambrian metasedimentary rocks; iii) alluvium and quaternary glacial deposits. The most important regional tectonic structure is the NNE-SSW Bragança-Vilariça-Manteigas fault zone (BVMFZ), which controls the thermomineral occurrences. The interpretation of Lansat images (channels 4, 6 and 7) show that the NE-SW tectonic structures prevail; NW-SE and E-W directions are also important (fig. 2b).This left-lateral strike-slip fault zone is one of the most important structures of the late-Variscan fault system network in NW Iberia (fig. 1). 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 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).

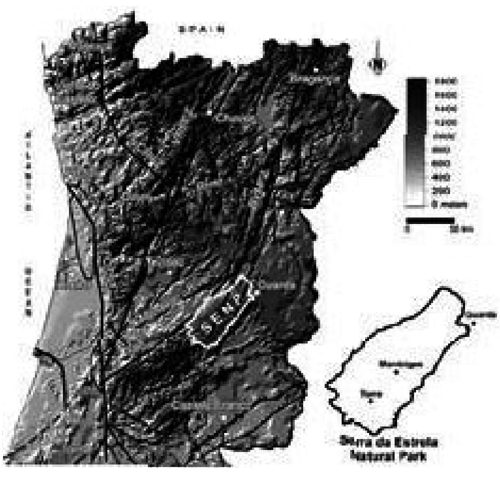


Figure 1
Morphotectonic features from Central Portugal, Serra da Estrela mountain region. Major faults: PCTSZ: Porto-Coimbra-Tomar strike-slip shear zone; VCRFZ: Vigo-Vila Nova de Cerveira-Régua fault zone; VRPFZ: Verin-Régua-Penacova fault zone; BVMFZ: Bragança-Vilariça-Manteigas fault zone; SLF: Seia-Lousã fault zone.

An important issue connected to the infiltration and aquifer recharge in the Serra da Estrela region consists on the identification of areas of prevailing fractured or porous circulation mediums (Espinha Marques et al., 2005). In particular, the porous mediums are dominant in the alluvium and quaternary glacial deposits as well as in the most weathered granites and metasedimentary rocks. Porous mediums usually occur at shallower depths (typically less than 50m). On the other hand, fractured mediums occur in poorly weathered rocks. Such mediums may be present very close to the surface (especially on granitic outcrop dominated areas, with thin or absent sedimentary cover) or bellow the referred porous geologic materials. The proposed regional hydrogeological units correspond nearly to the main geological characteristics (table 1): i) sedimentary cover, including alluvium and quaternary glacial deposits; ii) metasedimentary rocks, which include schists and graywackes; and iii) granitic rocks.

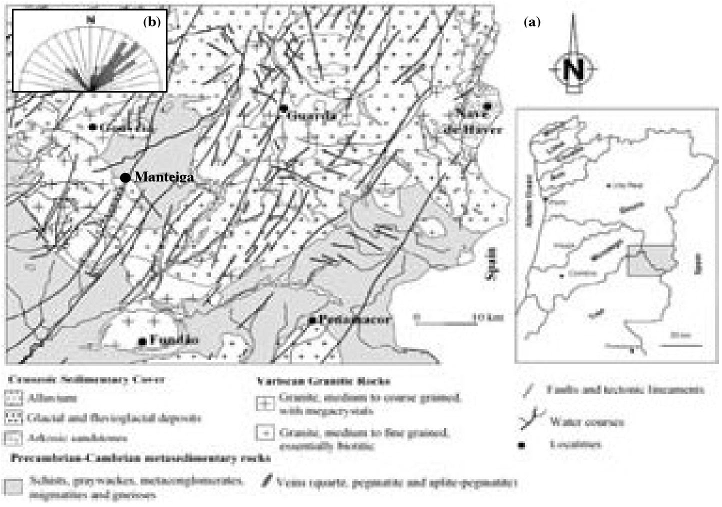


Figure 2
Geological framework. (a) geological map of Serra da Estrela region (adapted from Geological Map of Portugal, 1/500.000, SGP); (b) rose diagram from tectonic lineaments observed on Landsat images of the studied region.

Table 1
Main hydrogeological features from 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 Serra da Estrela (fig. 1) is the highest mountain in the Portuguese mainland (with an altitude reaching 1993m 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 on the local water cycle. The river Zêzere drainage basin upstream of Manteigas, corresponds to an area of ca. 28 km2 with an altitude ranging from 875m a.s.l., at the streamflow gauge measurement weir of Manteigas, to 1993m a.s.l., at the Torre summit (fig. 3). The relief of the study region is consists mainly of two major plateaus, separated by the NNE-SSW valley of the Zêzere river (Vieira, 2004): the western Torre–Penhas Douradas plateau (1450-1993m a.s.l.) and the eastern Alto da Pedrice–Curral do Vento plateau (1450-1760m a.s.l.). Late Pleistocene glacial landforms and deposits are a distinctive feature 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).

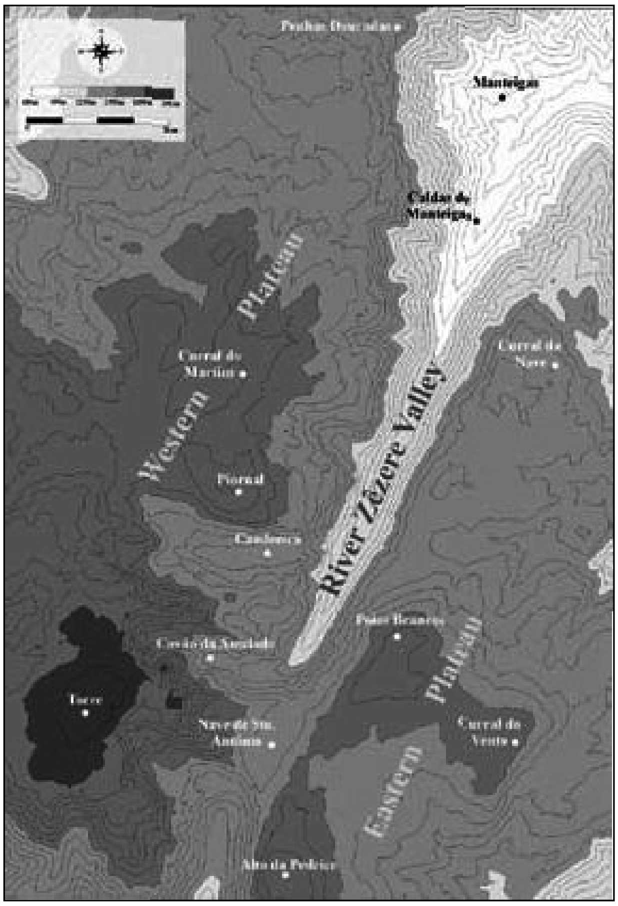


Figure 3 Hypsometric features of the river Zêzere drainage basin upstream of Manteigas.

The Serra da Estrela climate has Mediterranean characteristics, such as dry and warm summers; the wet season extends from October to May, with a mean annual precipitation of ca. 2500 mm in the Torre summit and more than 2000 mm in the plateaus (Daveau et al., 1997; Vieira & Mora, 1998). Precipitation seems to be mainly controlled by the slope orientation and the altitude. On one hand, the western side of the mountain presents a larger number of days with rainfall, but a slightly lower total amount than the eastern part, which in turn shows a smaller number of days with rain. On the other hand, a regional raise in the precipitation with the altitude is noticeable, even though, on a local scale, the spatial distribution of the precipitation may reveal great complexity. According to Vieira & Mora (1998), the warmest month is July and the coldest is January. Mean annual air temperatures are below 7°C in most of the plateaus 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 referred in earlier studies (e.g., Mora & Vieira, 2004). Since the snowfall above 1700m a.s.l. may represent a significant fraction of the annual precipitation, the aquifer recharge from snowmelt is being estimated through the use of isotopic methods and geomathematical modelling.

ISOTOPE HYDROLOGY AND HYDROGEOCHEMICAL APPROACH

Mountain river basins provide the best opportunity to understand the complexity of the relationships between climate and hydrology, as well as their impacts on the water quality at different elevation zones, under different settings (Chalise, 1994). Since Serra da Estrela Natural Park, as well as Zêzere river basin, extentds up to the highest elevation zones in Portuguese mainland, they provide unique places for integrated studies which will help in developing a scientific basis to understand and deal with the present-day hydrogeology and groundwater resources problems. Coupled isotopic and geochemical techniques have provided important information to answer the most usual addressed questions associated with the elaboration of a preliminary hydrogeologic conceptual circulation model of the Manteigas - Nave de Santo António -Torre sector (Serra da Estrela Natural Park - Central Portugal), namely: i) the sources of groundwater and location of recharge areas, ii) underground flow patterns, iii) age of thermomineral waters, and iv) water-rock interaction processes occurring at depth.

In this chapter we will discuss the use of stable isotope ratios (2H/1H and 18O/16O) to address questions associated with Caldas de Manteigas thermomineral waters, in particular the recharge and flow patterns, emphasising investigations using stable isotope data integrated with chemical and other relevant data (such as lithological or morphostructural characteristics) which usually produce important results.

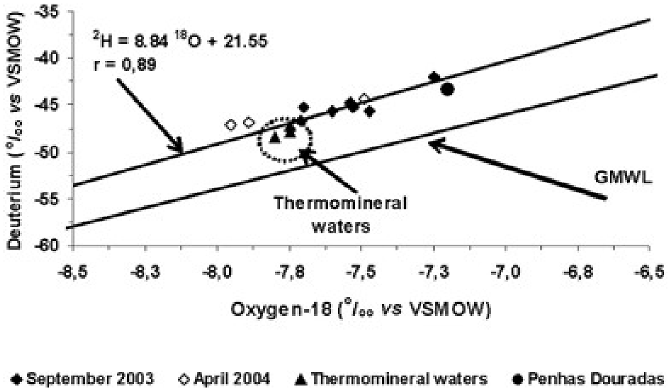
Isotope hydrology have been used for more than 25 years in the study of water flow resulting from snowmelt (see Kendall & McDonnell, 1998). The assessment of snowmelt contribution to stream and groundwater flow is complicated by isotopic fractionation during snow formation, accumulation, ablation and phase change during melt.

In fact, the isotopic content of snowpack is largely controled by the variations in the isotopic content of individual precipitation events (Kendall & McDonnell, 1998). For this reason, comprehensive sampling of meltwater, instead of snow, is generaly recommended for hydrological studies. Therefore, fieldwork campaigns were performed in April, after the begining of the snowmelt period in the studied region, and in September, which corresponds to the end of the Summer season.

The isotopic composition of the water samples collected at Serra da Estrela Natural Park (e.g. stream waters, shallow and thermomineral groundwaters) varies between -8.0 to -7.2‰ in $\delta^{18}O$ and between -48.5 to -42.0 ‰ in $\delta^{2}H$ (see fig. 4). In the diagram of figure 4, where the long term weighted mean value of precipitation collected at Penhas Douradas meteorological station (located at an altitude of 1380 m a.s.l.) is shown ($\delta^{2}H$ = -43.3‰; $\delta^{18}O$ = -7.20‰: in Carreira et al., 2004). One can observe a progressive depletion in heavy isotopes ascribed to the lowering of temperature with increasing elevation in mountain regions (the Global Meteoric Water Line is shown as reference).

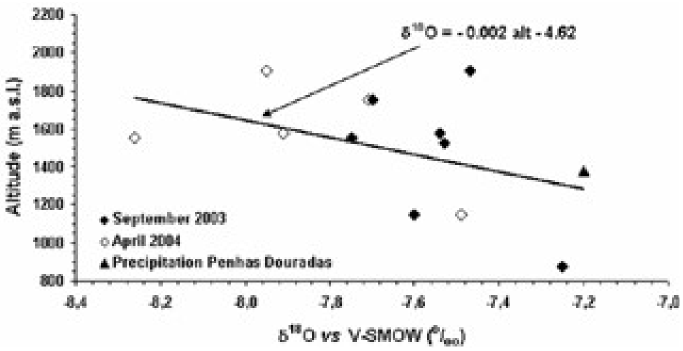
This so-called altitude effect allows the possibility to estimate the mean altitude of the recharge areas (fig. 5). The isotopic gradient for $\delta^{18}O$ in the study area is -0.20 ‰/100 m of altitude.

Figure 4
δ^2H vs $\delta^{18}O$ diagram for the studied waters.



The temporary storage of precipitation in the snowpack, and the subsequent melting, seems to greatly influence the hydrologic regimes at this high mountain area. Meltwater (collected from springs during the April/2004) is depleted in oxygen isotopes, when compared with the $\delta^{18}O$ values of waters collected in September 2003 (field campaign representing the end of Summer season) at the same springs (fig. 5). The determination of the age of a groundwater has strong implications on the groundwater resource management, contributing to its sustainable exploitation. Very low tritium contents (close to the detection limit) were observed on Caldas de Manteigas thermomineral waters (boreholes AC2 and AC3). These 3H signatures indicate long residence times ascribed to groundwater circulation reaching considerable depth. Tritium contents is consistent with the results of chemical geothermometers (Marques et al., 2005), which produce reservoir temperatures between 98°C and 103°C (given by the quartz geothermometer) indicating a maximum depth of about 3.8 km reached by the Caldas de Manteigas thermal water system, considering a geothermal gradient of about 25°C/km. On the other hand, the higher 3H values (between 2.0 and 5.5 TU) are associated to the local shallow groundwaters, indicating that they are recent, with relatively short residence times.

Figure 5
Relation of $\delta^{18}O$ to altitude of sampling sites (springs). Alt stands for recharge altitude.



For the elaboration of a preliminary hydrogeologic conceptual model of the Manteigas - Nave de Santo António - Torre sector, based on the isotopic composition of the groundwaters, we have estimated the following issues: i) the isotopic gradient for $\delta^{18}O$: the obtained value in the study area was -0.20 °/00/100 m of altitude; ii) the mean isotopic composition of the thermal waters in the region ($\delta^{18}O$mean = -7.8 °/oo vs VSMOW). Sustained by the isotopic composition variation, one can admit that the main recharge areas of the thermomineral subsystem are located above 1500 m a.s.l. The main recharge seems to occur laterally. The Bragança-Vilariça-Manteigas fault zone should play an important role in conducting the laterally infiltrated meteoric waters towards the discharge zone at the Caldas de Manteigas Spa. Caldas de Manteigas thermomineral waters (with output temperatures around 45°C) are characterised by the following main features: i) relatively high pH values (≈ 9), ii) TDS values usually in the range of 160 to 170 mg/L, iii) HCO_3 - Na facies, iv) the presence of reduced species of sulphur (HS- ≈ 1.7 mg/L), v) high silica values (usually around 50 mg/L) representing a considerable percentage of total mineralization and vi) high fluoride concentrations (up to 7 mg/L).

The strong HCO_3^- Na signatures of Caldas de Manteigas thermomineral waters indicates that the reservoir rock should be mainly the granite, being the thermomineral waters mineralization strongly dominated by the hydrolysis of plagioclases. In the studied region, the surface waters and shallow groundwaters (so called "normal waters") can be classified in two main groups, presenting the following characteristics:

- Group I) this group encloses the so-called "normal" surface (Zêzere river; sampling point close to the Caldas de Manteigas spas) and shallow groundwaters (Covão do Boi, Jonja, Paulo Luís Martins, Bisa and N. Srª. de Fátima spring waters),. All of these waters belong mainly to the HCO_3^-Na facies. Nevertheless, a relatively high Ca concentration was found in Bisa spring during the September 2003 field work campaign. Total mineralization should be regarded as a good indicator of the degree of water-rock interaction. Therefore, Zêzere river, Covão do Boi, Jonja and Paulo Luís Martins spring waters, presenting very low mineralization should be considered as representative of local recharge.
- Group II) this second group of waters encloses surface (Zêzere river – sampling points close to Covão da Ametade and Jonja stream) and shallow groundwaters (Nave de Stº António and Espinhaço de Cão spring waters). This group of waters is also characterized by relatively low mineralization, but presents clear Cl^-Na geochemical signatures. The Cl^-Na facies found within some of these waters could be ascribed to the local use of NaCl to promote snowmelt in the roads during the Winter season. These particular geochemical signatures found in Espinhaço de Cão spring can be clearly detected in the field through the higher electric conductivity values.

Besides, this second group of groundwaters samples is located in one of the potential recharge areas of the Caldas de Manteigas hydromineral system, which leads that in future fieldwork campaigns special emphasis will be put on the monitorization of the geochemical evolution of the locally infiltrated meteoric waters. In fact, environmental problems associated with the use of low-temperature thermomineral waters are different, in many aspects, from those of utilising high-temperature thermomineral resources. In this case, Caldas de Manteigas Spa are very dependent on both constant temperature and water quality. So, prevent mixing between deep thermomineral waters and locally recharged shallow groundwaters with signatures of anthropogenic contamination should be one of the main issues. The development of reliable management practices to preserve thermomineral water quality and remediation plans requires the elaboration of a reliable hydrogeologic conceptual model. Once detected the potential recharge areas, one must promote the identification of the local sources of pollution and the processes affecting (in each particular situation) local concentrations.

HYDROGEOLOGIC CONCEPTUAL MODEL

A model of a natural system is, by definition, a formal and simplified representation of a given reality. The formulation of a preliminary conceptual model (expressed by ideas, words and figures) is the foundation of subsequent mathematical models and strongly influences the type of computer code to be used and the design and priority of the site characterisation activities (NAP, 2001, Espinha Marques et al., 2004). In fact, the quality of the results obtained from the use of mathematical models is greatly influenced by the quality of the prior conceptual model.

The conceptualisation process implies the comprehension of the aquifer nature, its broad characteristics and the physical and chemical processes involved. Some of the most important features to consider include lithology, the geologic and geometric characteristics of the system's limits, the spatial variability of hydraulic parameters, hydrogeochemistry, surface-groundwater interactions, recharge, discharge, soil type, piezometry, among others. The hydrogeologic system existing in the river Zêzere basin upstream Manteigas comprises three main types of aquifers: i) shallow unconfined aquifers, hydraulically connected to the vadose zone; ii) shallow semi-confined aquifers; iii) a deep thermomineral aquifer. Waters from types i and ii aquifers have TDS ≈ 40 mg/L, pH ≈ 6 and temperature ≈ 10°C whereas thermomineral waters have TDS ≈ 160 mg/L, pH ≈ 9,5 and temperature ≈ 42°C.

The recharge of shallow aquifers seems to take place mostly in the plateaus; an additional part of the recharge may occur in the slopes of the Zêzere valley and its tributaries; the discharge areas are located in the Zêzere and Candeeira valley-bottoms and in the Nave de Santo António col (fig. 3).The recharge of the deep thermomineral aquifer seems to take place on more permeable zones of the granitic massif, associated to tectonic structures. Such zones correspond to the main tectonic valleys in the basin, wich simultaneously act as discharge areas of the shallow aquifer subsystem (fig. 6).

These recharge areas consist of a sedimentary layer of alluvium and quaternary glacial deposits overlying tectonised granite and receiving water influx both from vertical infiltration of precipitation (rain and snow) and lateral flow from the local shallow aquifers. As a result, the freatic surface lies very close to the surface during most of the year; in the case of Candeeira valley, a permanent lagoon results from these conditions.

Under these conditions, part of the groundwater flowing from the shallow aquifers reach the surface and outflows in springs or along the river bottoms, while another part circulates downward through the tectonic structures, eventually reaching the thermomineral reservoir (fig. 6). As pointed out by the morphostructural and isotopic data, the recharge areas should be the following (fig. 3): i) the NNE-SSW section of the Zêzere valley, corresponding to the main BVMFZ lineament; ii) the Nave de Santo António col, also lying over this lineament; iii) the Covão de Ametade and Candeeira valleys, corresponding to conjugate faults of the main structure.

The thermomineral discharge area is located ca. 800 m a.s.l., originating Caldas de Manteigas spa. The water ascending from the deep reservoir spurts in a location with distinct tectonic features: the intersection of the main NNE-SSW structure by WNW-ESE structures.

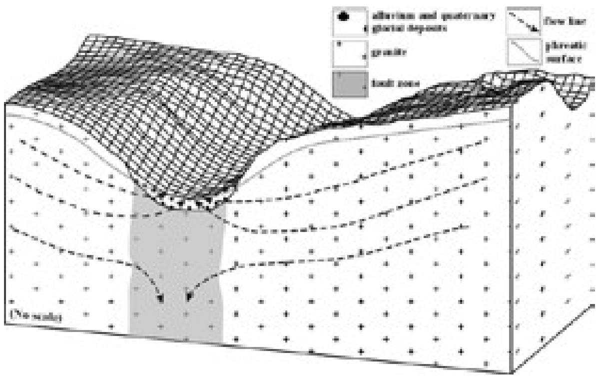


Figure 6
Scheme of the thermomineral aquifer recharge: a conceptual hydrogeological model.

Preliminary results of the water balance in the basin were achieved using VISUAL BALAN V2.0 (e.g., Samper et al., 1997, 2005) a code which performs daily water balances in the soil, the unsaturated zone and the aquifer, requiring a small number of parameters. The main inputs include precipitation and temperature data from Manteigas meteorological station (extrapolated to the whole basin, taking into account measured precipitation and temperature vertical gradients) for hydrologic years ranging from 1986-87 to 1994-95. Daily measurements of total runoff were used to test and calibrate the model. The model provides daily results of surface runoff, actual evapotranspiration, interception, interflow and groundwater flow (fig. 7).

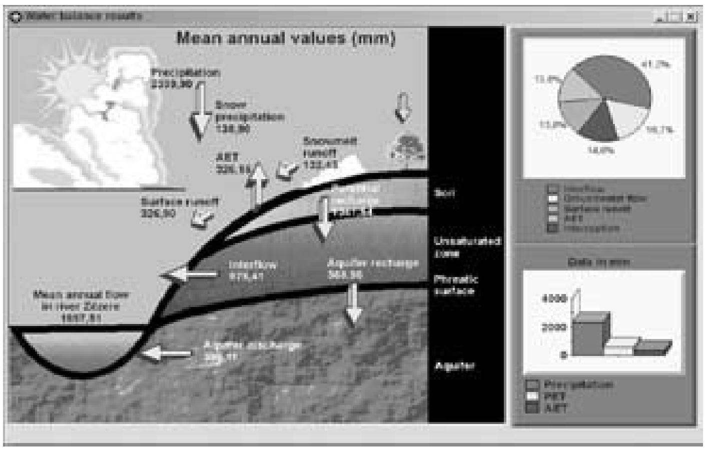


Figure 7
Main window of VISUAL BALAN showing average yearly results for the main hydrologic components in the study area. (AET: actual evapotranspiration; PET: potential evapotranspiration).

The results of the hydrologic model indicate that aquifer recharge is around 16% of the annual precipitation. This result is consistent with recharge estimates derived in other studies of hard-rock hydrogeologic systems in the Central-Iberian Zone. Carvalho et al. (2000) reported recharge rates from 14 to 17% of precipitation. Pereira (1999) obtained a value of 20%, whereas Lima (1994) gave a range from 14,6 to 21,7%.

CONCLUDING REMARKS AND OUTLOOK

The investigation of hydrogeologic systems takes place in progressive stages, which frequently overlap, and should be carried out within the framework of a hydrogeologic conceptual model of the system, that should be improved as more and more information is being collected. Each stage of investigation involves a number of operations to obtain, process and interprete field and laboratory data.

Morphostructural analysis and coupled isotopic and geochemical techniques have provided important information to the elaboration of a preliminary hydrogeologic conceptual model of the Manteigas - Nave de Santo António-Torre sector (Serra da Estrela Natural Park, Central Portugal), finding answers to the most usual addressed questions, namely: i) what is the origin of the waters? ii) where are the thermomineral aquifer recharge areas located? iii) which are the main water-rock interaction processes occurring at depth? iv) are the thermomineral waters at risk of antropogenic contamination as the result of mixing processes in the system?

The isotopic signatures of Caldas de Manteigas thermomineral waters, combined with the i) morphostructural data and ii) isotopic composition of shallow groundwater and precipitation samples, made it possible to identify potential three main recharge areas: i) the NNE-SSW section of the Zêzere valley; ii) the Nave de Santo António col and iii) the Covão de Ametade and Candeeira valleys. The recharge seems to occur mainly laterally. The Bragança-Vilariça-Manteigas fault zone should play an important role in conducting the laterally infiltrated meteoric waters towards the discharge zone at the Caldas de Manteigas Spa.

The identification of groundwaters that are sub-modern (recharged > 50 years ago) or older is an important issue for renewability of the systems characterisation. Groundwater dating should have into account the absence of 3H in the water sample (3H-free), which indicates no modern recharge component In the case of 3H-free groundwaters, dating techniques should involve long-lived radionuclides. Among the radioactive isotopes with a half-life higher than 103 years, carbon-14 (τ = 5730 years) represents the most important tool in groundwater dating. Future 14C measurements will be used to calculate the "age" of Caldas de Manteigas thermomineral waters.

This study also illustrates the importance of a multidisciplinary approach in order to provide a sustainable management for the strategic water resources existing in this region, namely thermomineral water and high quality drinking groundwater for bottling and domestic use.

ACKNOWLEDGMENTS

This study was performed under 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. PEF is grateful to Geodyn/POCTI-ISFL-5-32. We acknowledge M. J. Afonso (ISEP, Porto) for the revision of the manuscript.

REFERENCES

Afonso, MJ, Espinha Marques J, Marques JM, Carreira P, Carvalho JM, Marques da Silva M, Samper J, Veiga BP, Borges FS, Rocha FT, Fonseca PE, Gomes A, Araújo MA, Vieira GT, Mora C, Teixeira J, Almeida PG, Gonçalves JA and Chaminé HI, 2005. Hydrogeology of hard-rocks in the Portuguese Iberian Massif: Porto urban area and Serra da Estrela mountain region. In: Lopo Ferreira, JP 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).

Carreira PM, Araújo MF and Nunes D, 2004. Isotopic composition of rain and water vapour samples from Lisbon region – characterization of monthly and daily events. In: Research Co-ordination Meeting Isotopic composition in the mediterranean basin in circulation patterns and climate. IAEA-F3-RC-826-2, Vienna, Austria, in press

Carvalho, JM, Plasencia, N, Chaminé, HI, Rodrigues, BC, Dias, AG and Silva, MA, 2000. Recursos hídricos subterrâneos em formações cristalinas do Norte de Portugal. In: Samper, J, Leitão, T, Fernández, L and Ribeiro, L (eds.). Jornadas Hispano-Lusas sobre 'Las Aguas Subterráneas en el Noroeste de la Península Ibérica'. Textos de las Jornadas, Mesa Redonda y Comunicaciones, A Coruña. AIH-GE & APRH. Publicaciones ITGE, Madrid. pp. 163-171.

Chalise, SR, 1994. High mountain hydrology in changing climates: perspectives from the Hindu Kush-Himalayas. Developments in hydrology of mountain areas. In: Molnár, L, Miklánek, P and Mészáros, I. (eds.). Proceedings FRIEND AMHY Annual Report No.4, IHP-V, Technical Documents in Hydrology, 8: 23-31.

Daveau, S, Ferreira, AB, Ferreira, N, and Vieira, G, 1997. Novas observações sobre a glaciação da Serra da Estrela. Estudos do Quaternário, 1: 41-51.

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 and Rocha, FT, 2005. Hydrogeological study of a high mountain area (Serra da Estrela, Central Portugal): a multidisciplinary approach. Cadernos Laboratorio Xeolóxico de Laxe, A Coruña, 30: 145-166.

Kendall C and McDonnell, JJ, 1998. Isotope tracers in catchment hydrology. Elsevier, Amsterdam, 839 pp.

Lima, AS, 1994. Hidrogeologia de regiões graníticas (Braga, NW de Portugal). Universidade do Minho, Braga. 202 pp. (MSc Thesis).

Marques, JM, Espinha Marques, J, Carreira, PM, Aires-Barros, L, Carvalho, JM and Sodré Borges, FS, 2004. New approach on the hydrogeochemical signatures of Caldas do Moledo thermomineral system (N Portugal): implications for the hydrogeologic conceptual model elaboration. Cadernos Laboratorio Xeolóxico de Laxe, A Coruña, 29: 119-146.

Marques, JM, Carreira, PM, Espinha Marques, JM, Chaminé, HI, Fonseca, PE, Carvalho, JM & Cavaleiro, V, 2005. Pattern and spatial extent of thermal water flow in a high mountain area (Serra da Estrela, Central Portugal): a preliminary isotopic approach. In: Novák, M and Buzek, F (eds). Abstracts of the 6th International Symposium on Applied Isotope Geochemistry, Prague, p. 152-153.

Mora, C and Vieira, GT, 2004. Balance radiactivo de los altiplanos de la Sierra de Estrella (Portugal) en una mañana de invierno. Metodología y primeros resultados. Bol. R. Soc. Esp. Hist. Nat. (Sec. Geol.), Madrid, 99 (1-4): 37-45.

N.A.P - National Academy Press, 2001. Conceptual models of flow and transport in the fractured vadose zone. Washington, D.C. 374 pp.

Pereira, MR, 1999. Quantificação da recarga subterrânea em rochas fracturadas da bacia hidrográfica do Tua. In: Seminário Sobre Águas Subterrâneas. Laboratório Nacional de Engenharia Civil, LNEC, Lisboa.

Ribeiro A, Kullberg MC, Kullberg JC, Mannuppela G and Phipps S, 1990. A review of Alpine tectonics in Portugal: foreland detachment in basement and cover rocks. Tectonophysics, 184: 357-366

Samper, J, Soriano, G and Molinero, J, 1997. Las aguas subterráneas en Galicia: resultados en la cuenca piloto del río Valiñas. In: Hydrogeology of Hard Rocks, Associação Internacional de Hidrogeologia-Grupo Espanhol (AIH-GE). pp. 149-157.

Samper, J, Vera, MAG, Pisani, B, Alvares, D, Espinha Marques, J, Alberto Varela, A and Losada, JA, 2005. Hydrologic models and Geographic Information Systems for water resources evaluation: Application of GIS-BALAN to Atlantic basins in Spain and Portugal. In: Lopo Ferreira, JP 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).

Vieira, GT 2004. Geomorfologia dos planaltos e altos vales da Serra da Estrela. Ambientes frios do Plistocénico Superior e dinâmica actual. Universidade de Lisboa, 724p. + 1 mapa. (PhD Thesis).

Vieira, GT and 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, p. 26-36.