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Regional study of hard rock aquifers in Alentejo, South Portugal: methodology and results

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ABSTRACT Between 1997 and 2001 a Project called "Study of the Groundwater Resources of Alentejo Region" (ERHSA) was carried out in the region of Alentejo, southern part of Portugal. Great part of the area corresponds to igneous and metamorphic hard rocks. The exceptions are few areas of partly karstified crystalline limestones and a belt of sedimentary rocks on the western side. During ERHSA more than 7,000 data points were inventoried in hard rock aquifers. This extended study confirmed some results of previous studies, namely regarding the Gabbros of Beja Aquifer, and detected new productive or potentially productive areas within this region, namely the aquifers of the Charnokites of Campo Maior and Elvas, Pavia-Mora and the Évora-Montemor-Cuba. These last two systems mainly occur in gneissic or gneissic-migmatitic rocks, metamorphic volcanic-sedimentary complexes, and some tonalitic rocks.

The difference between the hard rock aquifers and the less productive sectors are clearly related with the intensity of the fracturing net and the deep and type of the weathering layer. This distinguishes the gabbros and other basic or intermediate rocks (more productives) from the less productive granites. The weathering layers of the first ones can go to 30 m deep, against the normal 2 m in granites.

The groundwater facies are mainly bicarbonate, except on the South part of Alentejo, where it is chloride-bicarbonate. The main cations are the magnesium, calcium and sodium, by this order, having most part of these waters a mixed cation composition between three or two of them. The Northern part of Alentejo has waters with low levels of mineralization (average less than 400 μS/cm of EC). On the contrary, the South part has clearly the most mineralized waters (average more than that 1,300 μS/cm of EC).

The future main task will be to conduct aquifer tests in order to have more hydrogeological parameters (transmissivity, permeability, and storage values), and try to understand the relation between instant yields, steady state flow, abstraction and aquifer parameters.

Keywords hard rock aquifers, regional study, mapping, groundwater quality, Alentejo, Portugal

Introduction

Between 1997 and 2001 a Project called "Study of the Groundwater Resources of Alentejo Region" (ERHSA, in Portuguese) was carried out in the region of Alentejo, southern part of Portugal (fig. 1). From the total area of Alentejo (26,931 km^2), 21,245 km^2 correspond to hard rocks. During the project more than 7,000 data points were inventoried in all hard rock aquifers of Alentejo. Most of them were wells or hand dug wells that are used basically for agriculture or domestic purposes. The most important abstractions in Portugal are related with agriculture. The actual number of public supply surface water points in Portugal is 459 (5 % of the origins) and 8,900 groundwater points (95 %). The total abstracted surfacewater volume is 627 hm^3 and the groundwater volume is 404 hm^3 (INAG 2006) for a total urban consumption of 529 hm^3. The diference is related with losses on the supply systems or other uses. The consumption per capiter is 169 L/inhab/day. Figure 2 (adapted from Ribeiro 2004) shows the distribution of ground- and surface water consumption in Alentejo, by municipalities.

Geomorphology, climatic conditions and infiltration rates

Alentejo is a flat area, at levels between 200 and 400 m a.s.l., with some little mountains, being the highest São Mamede, an elevation of about 1,200 m, on the northern part. All the other few mountains are less than 600 m high, and generally follow the Hercynian Orogeny geologic main direction: NW-SE. This plain is the result of the erosion that follows the Hercynian Orogeny and flattened the

Hercynian chain, letting some thin layers of an ancient erosion platform over the igneous and metamorphic Iberian craton.

The climatic conditions in Alentejo are Mediterranean type (except in the littoral west, which has the influence of the Atlantic climate), with the specific distribution of precipitation basically during winter, when the temperatures are low, and very low levels of precipitation in summer, when the temperatures are high (fig. 3).

Alentejo is a semi-arid region, with the precipitation going from about 450 mm per year until near or more than 800 mm on the highest mountains, as can be seen in figure 4 (Chambel et al. 1998).

Mendes (1989) estimated the values of the Budyko Aridity Ratio (BAR), which represents the ratio between mean annual potential evapotranspiration and mean annual precipitation (Sankarasubramanian & Vogel 2003). Regions where BAR is higher than the unit are boardly classified as dry, since the evaporative demand cannot be met by precipitation. Similarly regions where BAR is less than the unit are boardly classified as wet (Arora 2002). Figure 5 shows the BAR for Alentejo region. The littoral and the north are sub-wet. The continental area is semi-arid. This means that the desertification is taking place in the SE of Beja. The east region of Beja is one of the hottest areas of Europe continuous with the regions of Andaluzia and Extremadura in Spain.

Comparing the annual average precipitation isolines map with the BAR distribution map (fig. 4 and 5), it is possible to see the high correlation between the semi-arid climate and the precipitation deficit in the SE zone of Alentejo (Chambel et al 1998).

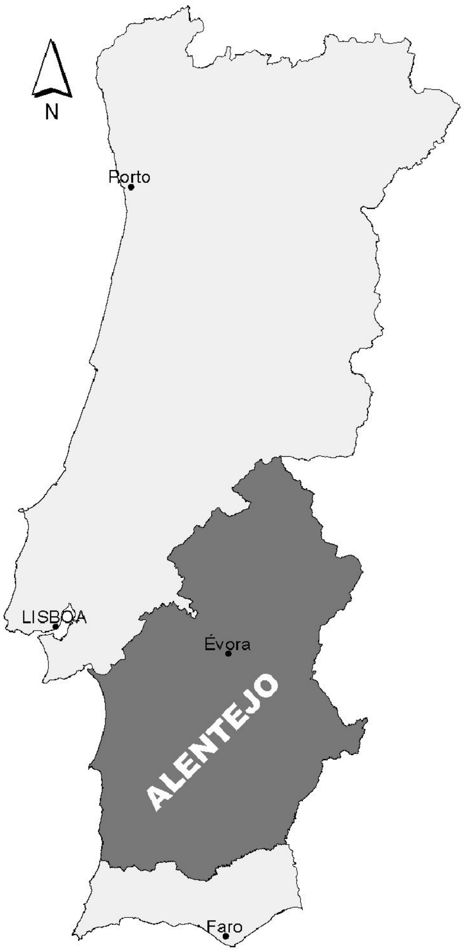

Fig. 1 – Location of Alentejo in Portugal.

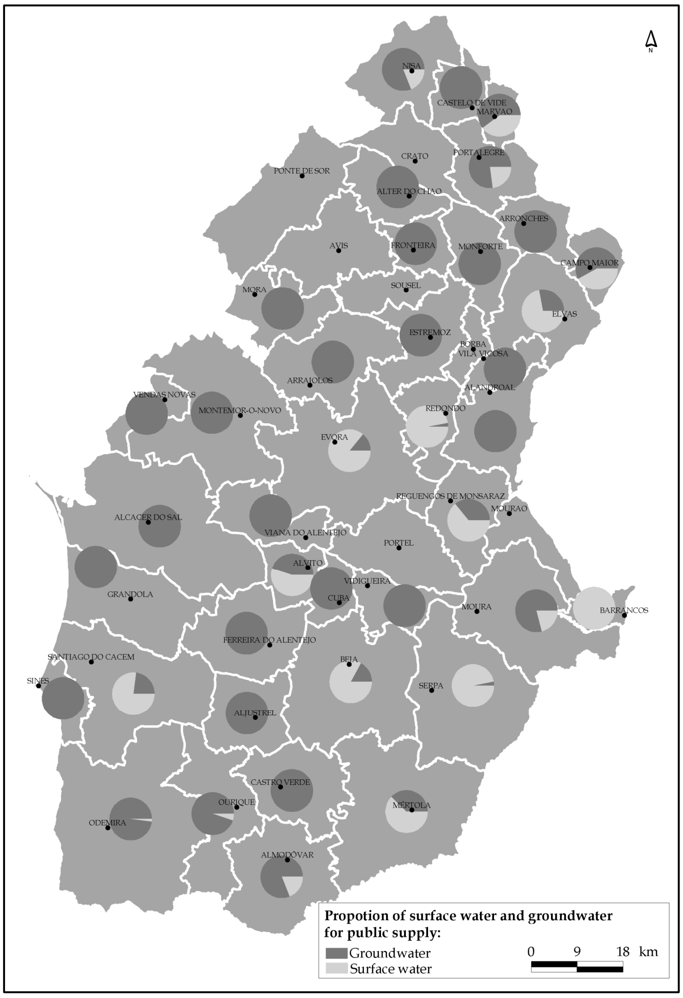

Fig. 2 – Percentage of groundwater uses for public supply in Alentejo (adapted from Ribeiro 2004).

The potential evapotranspiration is normally higher than 1,000 mm per year, causing a high water deficit in the soil.
It's a region of very warm and dry summers and the rainy season occurs on winter, with drought cycles sometimes during 2 or 3 consecutive years (Chambel et al. 1998). In Summer (June, July and August) the rain corresponds to only about 4 to 5 % of the annual precipitation. The agriculture requires intensive watering, due to high potential evapotranspiration during the productive cycle. The regional precipitation average in forty years, between 1958 and 1998 for all Alentejo, represented 604 mm (Chambel & Duque 1999). Henriques (1985) had studied the first order river basins of Alentejo (fig. 6) and esteemed the average annual precipitation and real evapotranspiration for each one (table 1). Also the infiltration values were calculated, showing that the average infiltration rates are between 2.8 and 4.8 % of the total precipitation in the Mira and Guadiana river basins, and 7.3 to 7.5 % in the Tejo and Sado river basins, involving in these last ones both sedimentary and hard rock aquifers. These values seems to be underestimated by the last works of Oliveira (in publication), who calculated the linear regression equation relating precipitation (P) with infiltration values in hard rocks using average annual base flow (Fb) values of 13 watersheds in Portugal:

$Fb = 0.5210*P - 284 = 0.5210*(P - 546)$ [Equation 1]

The correlation coefficient (r) for this equation is 0.989. Even so, the precedent equation considers two very high surface runoff/precipitation watersheds on the north of Portugal. More representative of the south conditions must be equation 2, that doesn't consider these two watersheds (Oliveira, in publication):

$Fb = 0.4107*P - 214 = 0.4107*(P - 520)$ [Equation 2]

but on this one r=0.860. This implies that results taken from these analysis are very much conditioned by the inexistence of a uniform distribution of watersheds' precipitations (Oliveira, in publication).
In both cases (equations 1 and 2), the average infiltration values are aproximately 8 % of the average precipitation values in Alentejo. This seems to be a better aproximation to real values, where the infiltration values on the less permeable hard rocks can be between 3 and 7 % and in the more productive ones, around 10 % of the annual precipitation values, as it was considered in ERHSA Project (ERHSA 2001), values that were also based on the preliminary works of Oliveira.

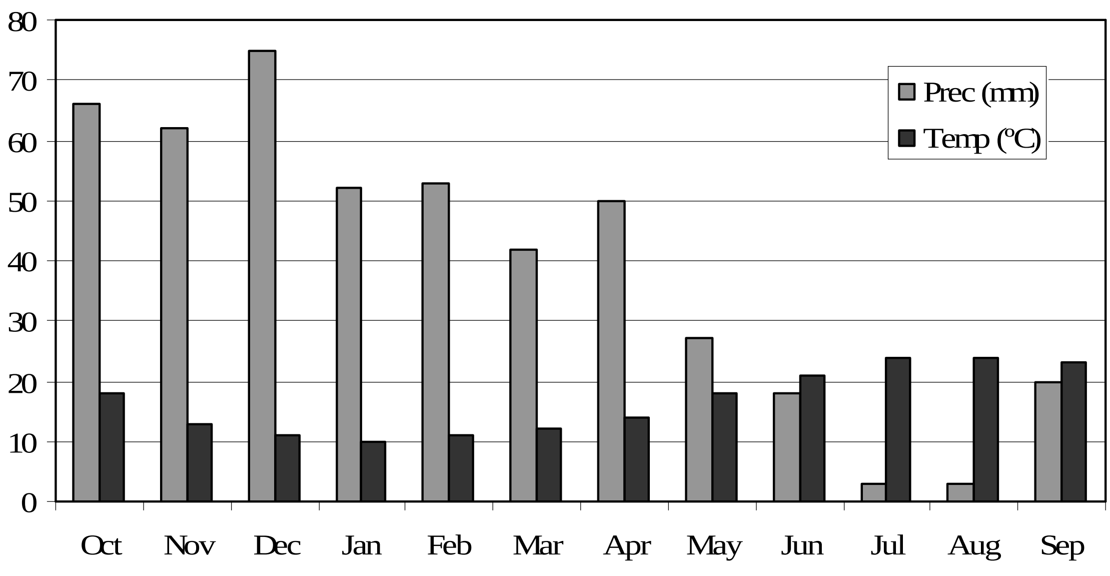

Fig. 3 – Average mensal precipitation and temperature distribution for the Alentejo climatic station of Vale Formoso, Mértola, South Alentejo (1971/72 to 1991/92 series) (Chambel 1999).

But Oliveira (in publication) also calculated the linear regression equations relating precipitation with infiltration values in some groups of hard rocks, using average annual base flow values. The equations were calculated for basins with igneous rocks, metamorphic rocks, both igneous and metamorphic rocks in the same basin, and igneous or metamorphic and sedimentary rocks also on the same basin. The resulting equations are presented in table 2, considering only the most representative values for

Alentejo region, which can be the basis for the calculation of infiltration rates in this area. The original table has more equations, involving basins in the north of Portugal with high rates of precipitation, not representative of Alentejo conditions. Also weathering conditions of the rocks and the infiltration rates can be very different from north to south.

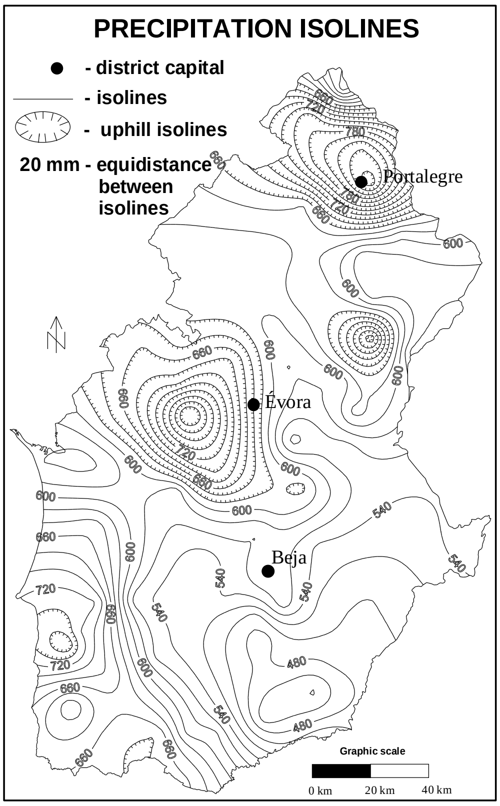

Fig. 4 – Projection of Annual Average Precipitation of Alentejo region.

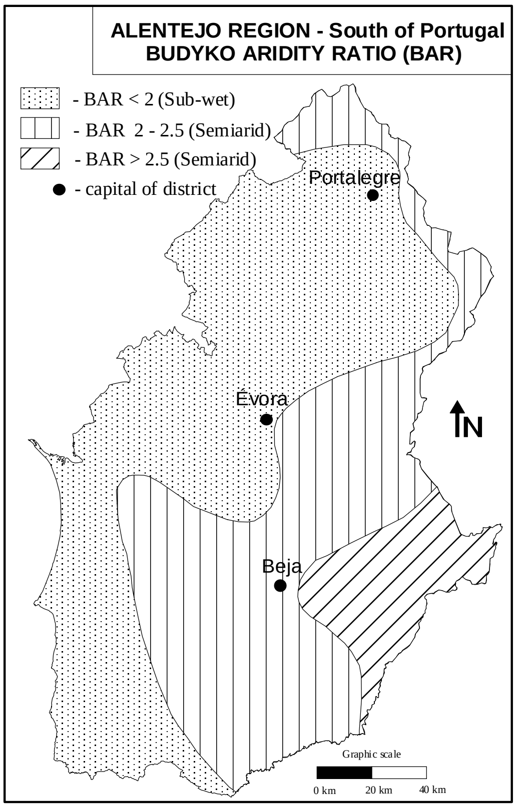

Fig. 5 – Budiko Aridity Ratio (BAR) distribution in Alentejo.

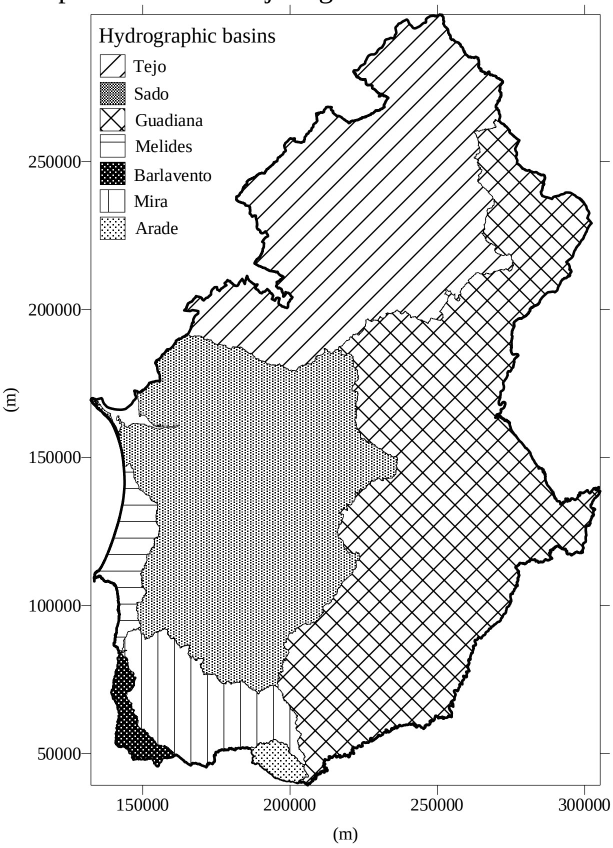

Fig. 6 – River basins in Alentejo region.

Geology

In terms of the geological features, the definition of the new aquifers was also based on the geo-structural divisions of Iberian Peninsula (fig. 7). The area is geologically complex, mainly the Ossa-Morena Zone.

The northern part of Alentejo (Centre-Iberian Zone) consists basically in schists and greywackes, with some quartzitic ridges, and highly compact granitic rocks. The schists and greywackes have a scarce soil, being many times skeletic, namely on the slopes near the most important rivers. The fractures are open only when quartz fractured veins are present. The quartzites form extensive narrow ridges without soil covering and present a dense net of open and clean fractures. The igneous rocks cross the border between Centre Iberian and Ossa-Morena Zones and have an incipient fracture net, with granite products of spherical jointing caused by weathering covering the

land, and only less than one to few meters of soil cover in some more weathered parts.
The Ossa-Morena Zone is formed by metamorphic and igneous rocks. The metamorphic ones are formed by schists, greywackes, gneisses, amphibolites, metamorphised volcanic rocks, and metamorphic limestones, in a great complexity, affected in some places by strong structural features that difficult the geological story interpretation of the area. The lithology of the igneous rocks is variable, going from granites to granodiorites, quartz-diorites, tonalitic rocks, diorites, gabbros, charnokites, andesites, etc. This knowledge is important on what concerns the analysis of the weathering layers deepness, directly associated to the aquifer volume, and to the water quality, that depends on the mineral constitution of the rocks: the most basic rocks have generally the most extended weathered layers.
The South Portuguese Zone has also its complexity. It is composed mainly by metamorphic rocks, including the so called "Pyrite Belt", a rich mineralised volcano-sedimentary complex. Most part of the area is formed by low metamorphic schists, greywackes, and conglomerates, with skeletic low productive soils.

Table 1 – Annual average of the precipitation, evapotranspiration and infiltration of the Alentejo main rivers basins (Henriques, 1985).

River Basin	**Area (km^2)**	**Precipitation (mm)**	**Evapotranspiration (mm)**	**Infiltration (mm)**	**Infiltration (% of precipitation)**	**Groundwater resources (hm^3/year)**
Tejo	9612	686	438	50	7.3	481
Sado	8217	678	480	51	7.5	411
Mira	1689	682	481	19	2.8	84
Guadiana	11855	581	426	28	4.8	593

Table 2 – Annual base flow linear regressions over annual precipitation by watershed groups (adapted from Oliveira, in publication)

Predominant lithological groups (watershed code)	**Equation**	***r***
Igneous rocks (19N08; 17L/01)	Fb=0.3987*(P – 428.1)	0.952
Metamorphic rocks (27I/01; 30G01; 22G/02; 06P/01)	Fb=0.1866*(P – 405.9)	0.736
Igneous + metamorphic rocks (20I13; 18L01; 19N01)	Fb=0.2394*(P – 458.0)	0.894
Igneous and/or metamorphic rocks + sedimentary (21F01; 18I01)	Fb=0.2246*(P – 330.5)	0.764
All watersheds (including 03D/01; 05E/01)	Fb=0.4703*(P - 521.0)	0.955

r = correlation coefficient

Investigation methodology

The lack of data on the hard rock aquifers in Portugal led to this study to establish differences of hydrogeological potential between different rock formations. This lack of data is more critical in hard rock aquifers because much drilling was done by companies characterized by lack of technical direction. In fact, this is due to the drilling techniques and to the economic lower values pay off that companies receive mainly when using the rotopercussion technique. On sandy aquifers, special techniques and more modern equipment are used and it is easier to find reliable reports.
Also much drilling was done without permission of legal authorities so that, in this case, the environment authorities did not receive the final reports and even when the reports were submitted, the information can be insufficient, erroneous, and even false.
Data should be collected and confirmed in the field in order to detect the misinformation or confirm the previous information. We collected data from governmental institutions and from drilling company archives, where it is sometimes possible to collect drilling data that were not recorded by the official authorities.

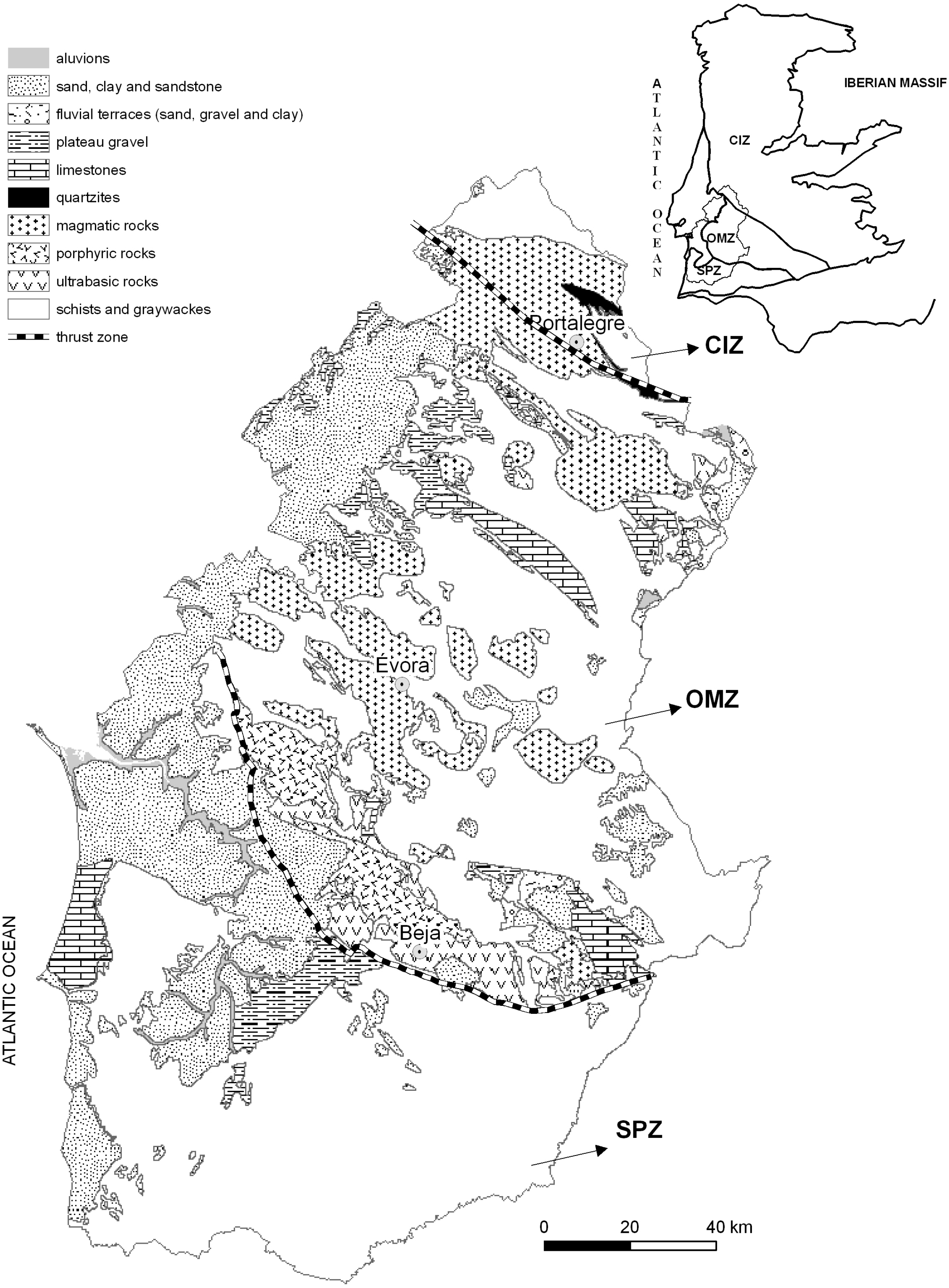

Fig. 7 – Simplified geology of Alentejo. CIZ – Centre-Iberian Zone; OMZ – Ossa-Morena Zone; SPZ – South Portuguese Zone.

With the names of the land owners, locations, or phone numbers, it was possible to identify location in the field and, talking with the owner, sometimes to obtain information about the initial yields, other information received from the drilling companies, such as drilling depths. Depths of the wells and position of pumping systems were recorded, when possible. Information about water use and the yields produced were also registered. Well withdrawals could sometimes be measured and information about how many hours per day or per week this water was used were recorded. All this information permits correction or confirmation of suspicious original data, particularly related to yields, lithological logs, etc.. Some aquifer tests were performed, but this was not easy due to the quantity of ropes, electric wires, etc., that are normally inside the wells, the lack of piezometric tubes, and also the opposition of many owners.

In order to compare the different hard rock lithologies in terms of hydrogeological productivity, the yield values registered on the reports were considered very important. These yields were obtained using compressed air directed to the bottom of the well on the final of the drilling work and letting stabilize the abstracted yield. This stabilization can happen after some 5 to 15 minutes (in most of the cases) to some few hours in special cases. In some wells with low productivities, this method causes well dewatering so this is not a recommended exploration yield, and have been considered as instant yields by some Portuguese authors (Carvalho 2000; Mira and Chambel 2001), due to narrow time limitation of this tests, many times not supported by the longer conventional aquifer tests using submersible pumps. The practice show that normally the abstraction yields must not be higher than 30 to 50 % of the measured instant yields. However, instant yield values can be used to compare with similar data on different aquifers. In this case, only the data from deep wells were considered. Unproductive wells were also inventoried, if data were available. This kind of information was obtained from company archives or directly from the land owners because these data are not usually registered by the public services.

Most of the ERHSA time and money was devoted to the data inventory, which was the basis for the final report and also for several papers and BSc, MSc and PhD theses. The database, which integrates hydrochemical data, maintains its importance for professionals studying the hydrogeology of the region.

The field work was organised with 5 to 7 hydrogeologists that coordinated the work on areas covering all Alentejo. More than 20 students participated on the data inventory and wrote their theses under instructions and supervision of the team. The task was to collect information on a minimum of one well in each 20 km^2 in homogeneous geologic formations and a maximum of wells in specific geologic complex areas and in new identified aquifers. In the first approach, all the possible construction data, yield, well deep and diameter, and the first field analysis of water temperature, EC and pH were recorded.

Based on this initial database, almost 2,000 data points were object of chemical and physical laboratory analyses. These represented deep wells, hand dug wells, and some springs.

EC and other hydrochemical parameters were studied to evaluate the spatial distribution of hydrochemical facies that could help to delineate new aquifers.

All the information was finally put on an easily accessible database to permit interface with hydrogeology software, data management, and use of geographic information systems (GIS). The final project maps were organised on GIS, to allow the use of geographic bases in future development work.

Results

Generally the hard rock aquifers of this area are considered of low productivity, with the recognized exception of the crystalline limestones, which are sometimes karstified. The metamorphic and igneous rocks have only a few meters of weathered layers (0 to 6 m deep) and a very incipient fracture system under these layers. More deeply, the bedrock has only a scarce net of fractures, where these fractures can be separated by tens or hundreds of meters under depths between 60 m (generally in igneous rocks) and more than 200 m (more likely in metamorphic rocks). In igneous rocks the wells have generally some water on the first 60 m deep, and it’s rare to find new productive levels under this depth. In metasedimentary rocks the probability of occurrence of new productive levels with depth increases in relation with igneous rocks, being equally possible to get water on the first 100 m or on the following 100 ones.

Even so, an aquifer with special characteristics was already known in Alentejo (fig. 8): the Gabbros of Beja Aquifer (Paradela & Zbyszewski 1971) and it has been object of some thesis in the last years

(Duque 1997; Duque 2005; Paralta 2001). Paralta is also preparing his PhD thesis on the same area. Here there is a median thickness of 26 m of weathered or fractured gabbro-dioritic rocks that can reach up to 80 m deep, with the groundwater flowing in fractures that are enlarged by chemical water attack. In 1971 in this aquifer, hand dug wells with a maximum of 20 m deep, much of them with 1.5 m high galleries in the bottom or at different levels under the piezometric level, and other wells with a maximum of 50 m deep, were used to abstract groundwater for human supply. The yields could reach 8 L/s, exceptionally 10 L/s, with the production clearly decreasing during the dry season. More recently, Duque (2005) has shown that the real productivity (including unproductive wells), for 1,067 well data, was about 3.34 L/s (average), 1.53 L/s (median) till a maximum of 36 L/s. The high productive levels vary between 1 and 78 m deep, being the major productive levels between the 12 and 20 m. Based on 1,030 well logs, the aquifer shows an average of 2 m of topsoil clays, a total weathered layer of 12 m and a fractured net till 27 m deep.

In fact, the difference between the less productive hard rock aquifers and some more productive ones are basically the fracture density and, more importantly, the total weathered thickness. More than 10-15 m of weathered layers create a more productive aquifer, based on a higher porosity and an easier interconnection between fractures. That is why the most ancient rocks, subject to more orogenic processes, and affected by more recent orogenies are the most productive hard rock aquifers in Alentejo.

During ERHSA studies, the information confirmed the existence of other aquifers with characteristics similar to those of the Gabbros of Beja (ERHSA 2001). One of the main conclusions was that gabbros, gneisses, migmatitic gneisses, some volcano-sedimentary, and tonalitic rocks were more productive than the other lithologies of the region. Three new aquifers were identified (fig. 8 and table 3), now designated as:

- Charnokites of Campo Maior and Elvas
- Pavia-Mora
- Évora-Montemor-Cuba, subdivided in 5 different sectors: Évora, Montemor, Escoural, Cuba-S. Cristóvão, Vidigueira-Selmes

On the remainder areas, some low productive sectors were identified (fig. 8 and table 3):

- Amieira-Montalvão
- S. Mamede
- Granites of Nisa, Portalegre and Santa Eulália
- Ossa-Morena Zone (OMZ)
- South Portuguese Zone (SPZ)

The characteristics of all the aquifers and low productive sectors are defined on table 3.

Table 4 shows that the most productive aquifers have an average of instant yield values higher than 4.5 L/s and median values higher than 1.9 L/s (Évora and Montemor sectors of the Évora-Montemor-Cuba Aquifer).

The Escoural sector of the Évora-Montemor-Cuba Aquifer, the Gabbros of Beja Aquifer and also the new identified aquifer of the Charnokites of Campo Maior and Elvas and Pavia-Mora have average instant yield values of more than 3 L/s. Only the Cuba-S. Cristóvão and Vidigueira-Selmes sectors seem to have lower values with average values over 2.5 L/s.

The low productive sectors of Amieira-Montalvão, S. Mamede and of the Granites of Nisa, Portalegre and S. Eulália show average instant values less than 2 L/s, the last one with only 0.72 L/s.

The low productive sectors of Ossa-Morena Zone and South Portuguese Zone display average values respectively of 2.01 and 2.42 L/s, which means that there are, in these sectors, some productive areas linked to fractured zones, like the Pyrite Belt in South Portuguese Zone, that need more investigation.

Dividing the instant yield values by the depth of the wells, the same conclusion is possible (table 5): the Évora, Montemor and Cuba-S. Cristóvão sectors of the Évora-Montemor-Cuba Aquifer and the Gabbros of Beja Aquifer have clearly higher productivities (more than 0.08 L/s/m drilled) when compared with Escoural and Vidigueira-Selmes sectors (more than 0.05 L/s/m drilled) or the Charnokites of Campo Maior and Elvas or Pavia-Mora sectors, under 0.03 L/s/m drilled. The other sectors, considered of low productivity, show average values under 0.03 L/s/m drilled.

The depth of the wells can be a measure of the depth of the weathering zone, but also an indication of the difficulties to find water during drilling. Because the drillings are normally not assisted by hydrogeologists, the decision to stop is responsibility of the land owner and commanded many times by the necessities on water, by economic reasons, or intuition.

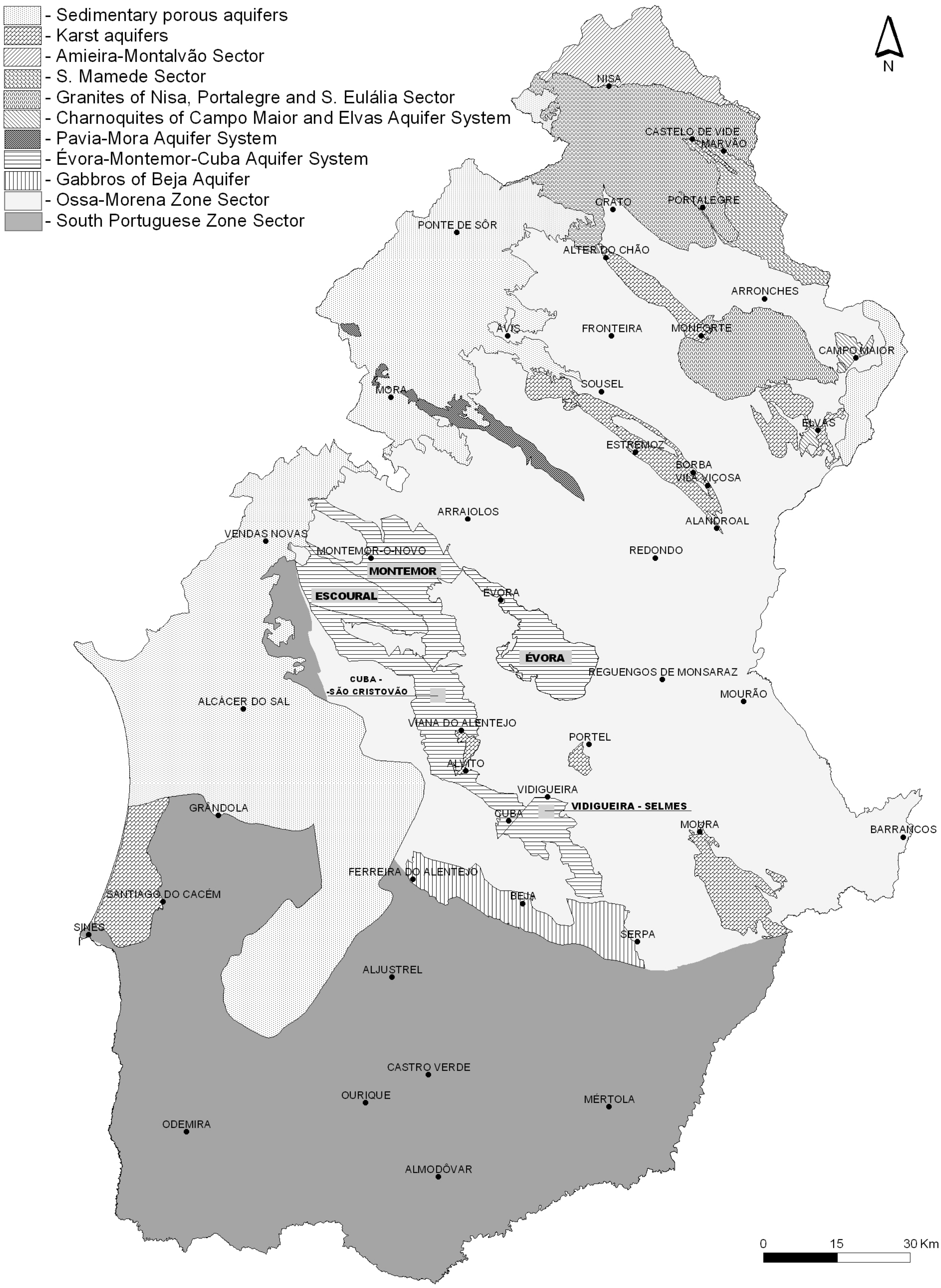

Fig. 8 - Hydrogeological cartography of Alentejo region, Portugal (ERHSA 2001).

As can be seen on table 6, average values higher than 60 m deep are present of the sectors of Montemor, Escoural and Vidigueira-Selmes of the Évora-Montemor-Cuba Aquifer, on the Pavia-Mora Aquifer, on the less productivity sectors of Amieira-Montalvão, S. Mamede, OMZ and SPZ. The more productive sectors of Évora, Cuba-S. Cristóvão, the Gabbros of Beja Aquifer, the Charnokites of Campo Maior and Elvas and the low productivity sectors of the Granites of Nisa, Portalegre and Santa Eulália present average values lower than 50 m, the first ones probably due to high productivities on the first tens of meters and the last one because it is practically impossible to get water under some few tens of meters deep. The Gabbros of Beja present the lowest of all the medium values (38.1 m). The justification to these results is on the fact that the most productive systems have a weathered and fractured rock layer on the first 20-40 m. Thus, prospection below this depth is less productive. Also the low productive areas of granites have the water mainly on the first tens of metres, many times on the first 10 m, motif why the prospection is not so deep in those areas. On the contrary, the schists can have productive fractures at any deep, at least on the first 200 m, so it’s possible to expect these wells to be deeper.

Aquifer tests in some wells of these areas had show that the transmissivities in the gneissic-migmatitic complex of Évora Sector are between 37 and 373 m^2/day (Fialho et al. 1998; ERHSA 2001). In 227 aquifer tests in the Gabbros of Beja Aquifer the median value was 40.8 m^2/day and the maximum 432 m^2/day (Duque 1997; Duque & Almeida 1998; Duque 2005). Values between 0.6 e 7 m^2/day were registered in granodiorites and quartzodiorites of the low productive area of OMZ. Transmissivity on schists and greywackes of the low productivity area of SPZ are between 0.07 and 18.3 m^2/day in 9 aquifer tests on schist and greywacke aquifers on the south-eastern part of the area (Chambel 1999). More recent aquifer tests, on the low productive sector of Amieira-Montalvão, show transmissivities between 0.8 and 12 m^2/day on 5 aquifer tests on previous wells that were done without any scientific assistance, and between 15.2 and 60.6 m^2/day on aquifer tests of new three wells located with geologic and hydrogeologic investigation and geophysic methods. Three aquifer tests on the less productive sector of Granites of Nisa, Portalegre and Santa Eulália led to results between 0.2 and 5.3 m^2/day on the previous wells and 30.8 m^2/day on the only productive well in three new excavated boreholes (two were considered unproductive, in spite they have some water, between 1,000 and 2,500 m^3/h of instant yield values). Transmissivity values obtained in some common aquifer tests are also presented on table 4, in order to compare with instant yield value statistics.

Table 3 – Main geologic and hydrogeologic characteristics of aquifers and low poductivity sectors of Alentejo region, South Portugal (ERHSA 2001).

Aquifers and Hydrogeologic Sectors		Lithologic characteristics	Aquifer characteristics, weathering and fracturing
Aquifers			
Évora-Montemor-Cuba	Évora Sector	Gneisses, migmatites, granodiorites and quartz-diorites	Maximum of 30 m, generally not more than 20 m of weathered and fractured rock, free to semi-confined aquifer
	Montemor Sector	Migmatites, migmatitic gneisses, some granites, tonalites and hornfels	Similar to Évora sector
	Escoural Sector	Leptinites, black quartzites, acid and basic meta-volcanites, meta-psamites, schists with high levels of quartz veins, calco-schists, crystalline limestones and amphibolites	Fractures occur until 80 m depth in some special rocks (quartzites, amphibolites), where the wells are more productive; low extension of the weathered zone; similar to the other sectors on the remaining lithologies
	Cuba-S. Cristóvão Sector	Gabbrodiorites, granitic ortogneisses, a metapelitic-psamitic sequence, leptinites, black quartzites, metabasites and ortogneisses	Litologies are similar to other sectors of Évora-Montemor-Cuba Aquifer, but there are a big lack of information on this sector
	Vidigueira-Selmes Sector	Basic volcanites, granodiorites, gabbrodiorites, hornfels	Fractures untill 20-30 m depth, free to semi-confined aquifer, with 4 to 8 m of weathered layer
Gabbros of Beja		Gabbros, diorites, serpentinites, meta-trondhejmites, meta-basalts, flasergabbros, amphibolites, piroxenites, dunites and peridotites	Average of 2 m of topsoil clays, an average of total weathered layer of 12 m and an average of the fractured net till 27 m deep; free to semi-confined aquifer
Charnokites of C. Maior and Elvas		Gabbro metamorphized rocks, piroxenites, anortosites, diorites, quartz-gabbros and hornblendites in two different spots	Extremely fractured and weathered rocks; no indications about the weathered zone extension
Pavia-Mora		Gneissic granitic and granitic gneissic rocks, granites, gabbros and diorites; the metamorphic rocks are less significant and represented by leptinitic gneisses, amphibolites, micaschists and crystalline limestones	Fractured media, with weathered layers generally less than 6 m deep
Low Productivity Sectors			
Amieira-Montalvão Sector		Mainly phylites, meta-greywackes, pelitic schists, meta-conglomerates and hornfels	Skeletic soils; great hydrogeologic importance of the presence of fractured quartz veins and faults filled with quartz
S. Mamede Sector		Mainly schists, lidites, quartzites, sandstone, clay schists, volcanoclasts, conglomerates and arkoses	Skeletic soils; great importance of the presence of fractured quartz veins and faults filled with quartz
Granites of Nisa, P. and S. E. Sector		Granitic rocks	At surface, the products of spherical jointing caused by weathering are visible, being the weathered zone in general terms less than 2 m deep and the fracture system very sparse
Ossa Morena Zone Sector		Mainly schists and greywackes, and different kinds of igneous rocks, granites, granodiorites, quartz-diorites, tonalites, diorites, andesites, some gabbros, but also volcanic or porphyritic rocks	Low extension of weathered layer and great importance of the presence of quartz fractured veins linked to groundwater production
South Portuguese Zone Sector		Mainly low metamorphic schists, greywackes and volcano-sedimentary complexes	In most of the area, skeletic soils, low extension of the weathered layer and a great importance of the presence of quartz fractured veins linked to groundwater production

Table 4 – Statistical results of instant value yields of the different sectors and aquifers in Alentejo region. The sectors of Évora, Montemor, Escoural, Cuba-S. Cristóvão and Vidigueira-Selmes are part of the Évora-Montemor-Cuba Aquifer. Values from ERHSA 2001, Ghira 2002, Espada 2003, Furtado 2004, Ramalho 2004, Duque 2005, Ferreira 2005, Monteiro 2005, Rodrigues, in publication.

Statistics of instant yield	**Average (L/s)**	**Median (L/s)**	**Minimum (L/s)**	**Maximum (L/s)**	**Standard deviation**	**Number of deep wells with instant yield values**	**Number of deep wells**	**Total number of wells**	**Trsnsmissivity values range (m^2/day)**
Aquifers									
Évora Sector	5.54	3.33	0	27.8	6.02	187	205	322	37-373
Montemor Sector	4.47	1.94	0	41.66	6.92	89	201	413	
Escoural Sector	3.97	1.53	0	26.39	6.07	30	63	144	
Cuba-S. Cristóvão Sector	2.75	1.11	0	26.39	4.19	280	313	417	
Vidigueira-Selmes Sector	2.61	1.11	0	28.75	4.76	88	112	229	40
Gabbros of Beja	3.33	1.52	0	36.1	4.82	1,067	1,059	1,798	1.7-432
Charnokites of C. Maior and Elvas	3.03	1.67	0.42	33.3	5.16	40	43	53	
Pavia-Mora	3.20	1.38	0	27.8	5.79	30	44	63	
Low Productivity Sectors									
Amieira-Montalvão Sector	1.64	1.39	0.28	6.94	1.62	15	19	53	0.8-60.6
S. Mamede Sector	1.46	1.25	0.06	4.00	0.88	31	56	74	
Granites of Nisa, P. and S. E. Sector	0.72	0.48	0	5.56	0.99	89	330	627	0.2-30.8
Ossa Morena Zone Sector	2.01	1.20	0	40	3.00	935	2,135	5,183	0.6-7
South Portuguese Zone Sector	2.42	1.49	0	19.4	2.68	538	927	1,402	0.07-18.3

Table 5 – Comparative instant yield by metre drilled on the aquifer and other hydrogeologic sectors of Alentejo. The sectors of Évora, Montemor, Escoural, Cuba-S. Cristóvão and Vidigueira-Selmes are part of the Évora-Montemor-Cuba Aquifer. Values from ERHSA 2001, Ghira 2002, Espada 2003, Furtado 2004, Ramalho 2004, Duque 2005, Ferreira 2005, Monteiro 2005, Rodrigues, in publication.

	L/s/m drilled	**Number of deep wells with both yield and depth values**
Aquifers		
Évora Sector	0.1238	180
Montemor Sector	0.0864	80
Escoural Sector	0.0604	30
Cuba-S. Cristóvão Sector	0.0897	223
Vidigueira-Selmes Sector	0.0590	86
Gabbros of Beja	0.0874	1,059
Charnokites of C. Maior and Elvas	0.0275	11
Pavia-Mora	0.0197	18
Low Productivity Sectors		
Amieira-Montalvão Sector	0.0210	8
S. Mamede Sector	0.0274	21
Granites of Nisa, P. and S. E. Sector	0.0110	66
Ossa Morena Zone Sector	0.0289	771
South Portuguese Zone Sector	0.0265	435

About 2,000 water-quality analyses were made on all the Alentejo hard rock area. The results show that the north area (Centre-Iberian Zone) has the less mineralised groundwaters (Amieira-Montalvão Sector, S. Mamede Sector and Granites of Nisa, Portalegre and S. Eulália Sector), and the South Portuguese Zone and Pavia-Mora Aquifer have the higher mineralization rates (table 7). The groundwater facies change with the different geologic units (table 7):

Table 6 – Statistical results of the depth of the drillings and deep wells in the aquifer and sectors of Alentejo. The sectors of Évora, Montemor, Escoural, Cuba-S. Cristóvão and Vidigueira-Selmes are part of the Évora-Montemor-Cuba Aquifer. Values from ERHSA 2001, Ghira 2002, Espada 2003, Furtado 2004, Ramalho 2004, Duque 2005, Ferreira 2005, Monteiro 2005, Rodrigues, in publication.

Total depth	**Average (m)**	**Median (m)**	**Minimum (m)**	**Maximum (m)**	**Standard deviation**	**Number of wells with data on depth**	**Number of deep wells**	**Total number of wells**
Aquifers								
Évora Sector	44.87	40	8	130	21.08	180	205	322
Montemor Sector	61.47	60	15	151	28.63	138	201	413
Escoural Sector	77.81	75	35	150	28.05	36	63	144
Cuba-S. Cristóvão Sector	55.58	48.5	5	215	36.93	223	313	417
Vidigueira-Selmes Sector	72.12	70	20	177	28.70	107	112	229
Gabbros of Beja	38.1	34	2	140	18.30	1,059	1,059	1,798
Charnokites of C. Maior and Elvas	42.27	46	22	75	19.23	11	43	53
Pavia-Mora	68.63	67	31	108	19.70	26	44	63
Low Productivity Sectors								
Amieira-Montalvão Sector	75.1	80	43	120	27.90	9	19	53
S. Mamede Sector	63.80	60	16	262.75	40.85	34	56	74
Granites of Nisa, P. and S. E. Sector	54.78	56.5	2	187	33.87	152	330	627
Ossa Morena Zone Sector	68.44	69	10	205	30.18	772	2,135	5,183
South Portuguese Zone Sector	65	65	0	200	25.16	662	927	1,402

- In all the aquifers and less productive sectors, the facies are bicarbonate, except on the South Portuguese Zone, the Alentejo area with lower precipitation values and highest evapotranspiration rates, where the main anion is the chloride, immediately followed by the bicarbonate.
- Most part of the aquifers have magnesium as the main cation, but very similar contents of calcium and sodium occur. Magnesium is often related with basic igneous and metamhorphic rocks, as it can be seen by the crossing of information between tables 3 and 7. In some cases, calcium is the main cation, but always closely followed by another one (sodium or magnesium); in two cases, sodium is the main cation, followed by magnesium (Pavia-Mora and South Portuguese Zone).
- Nitrate levels are high in practically all the aquifers because normally these correspond to the best soils and main irrigation areas in Alentejo. This is due to the fact that the better aquifers are those where weathering is more intense and the best quality soils exist. Together with the water availability, the nitrate use is more intensive there. The less productive sectors have generally lower nitrate average values.

Concluding remarks

This large study (ERHSA 2001) allowed to confirm some previous aquifer informations regarding the Gabbros of Beja Aquifer and to detect new productive or potentially productive areas on this region, the aquifers of the Charnokites of Campo Maior and Elvas, Pavia-Mora and Évora-Montemor-Cuba. There are also some field indicators that some regions of porphyries, considered in the low productivity area of the Ossa-Morena Zone can also be very interesting aquifers, where fracturing is important.

The main aquifers occur in gabbros, gneissic or gneissic-migmatitic rocks, metamorphic volcanic-sedimentary complexes, and some tonalitic rocks, particularly where these rocks were affected by the Hercynian Orogeny. Understanding the vertical extension of the weathering materials and the fracture networks is essential to define the best aquifers in the hard rocks of Alentejo, and perhaps elsewhere. This paper also reflects all the new data collected after ERHSA, representing some hundreds of new well data.

Table 7 – Hydrochemical characteristics of Alentejo groundwaters (ERHSA 2001), with the avarege values for the different parameters (n – number of samples).

Aquifers and Hydrogeologic Sectors	**Field EC**		**Field pH**		**Alcalinity**		**Total Hardness**		**CO_2**		**SiO_2**		**NO_3**	
	n	**μS/cm**	**n**		**n**	**mg/L**	**n**	**mg/L**	**n**	**mg/L**	**n**	**mg/L**	**n**	**mg/L**
Aquifers														
Évora Sector	127	868	80	7.62	49	249	49	368	48	7.4	49	27.6	48	79
Montemor Sector	237	484	241	6.97	53	143	53	187	51	30.1	50	28	53	33.8
Escoural Sector	96	585	98	7.16	18	179	18	262	18	24.1	17	34.3	18	33.4
Cuba-S. Cristóvão Sector	118	849	122	7.45	36	231	35	323	35	18.5	32	27.1	36	42.4
Vidigueira-Selmes Sector	127	927	127	7.7	23	266	23	350	22	10.8	20	23.2	21	42.9
Gabbros de Beja	79	820	80	7.53	79	241	79	347	72	20	71	21.4	79	57.9
Charnokites of C. Maior and Elvas	17	816	17	7.78	6	265	6	343	2	8.6	6	36.6	5	64.9
Pavia-Mora	32	1,401	21	7.21	14	257	14	435	14	23.7	9	35.8	14	52.3
Low Productivity Sectors														
Amieira-Montalvão Sector	35	372	35	6.6	13	56	13	58	12	5.8	13	29.5	13	2.5
S. Mamede Sector	28	168	28	6.47	19	87	19	87	18	20	19	13	16	12.3
Granites of Nisa, P. and S. E. Sector	319	253	319	6.5	102	226	101	263	98	15.4	102	31.5	104	14.8
OMZ Sector	2,754	745	2,438	7.37	718	214	714	295	661	17.6	704	25.9	722	39.2
SPZ Sector	870	1,311	775	7.04	577	190	577	367	547	23.8	577	16.2	530	25.7

Aquifers and Hydrogeologic Sectors	**Ca**		**Mg**		**Na**		**K**		**Cl**		**SO_4**		**Corrected HCO_3**		**Facies**
	n	**epm**	**n**	**epm**	**n**	**epm**	**n**	**epm**	**n**	**epm**	**n**	**epm**	**n**	**epm**	
Aquifers															
Évora Sector	49	3.38	49	3.76	49	3.13	49	0.11	49	2.79	49	0.56	48	9.57	C-Mg-Ca-Na
Montemor Sector	53	1.84	53	1.84	50	1.68	50	0.04	53	1.52	53	0.32	52	5.46	C-Mg-Ca-Na
Escoural Sector	18	2.51	18	2.73	17	1.93	17	0.06	18	2.34	18	0.43	18	7.01	C-Mg-Ca-Na
Cuba-S. Cristóvão Sector	36	3.47	35	3	36	3.07	36	0.08	36	2.82	36	0.5	36	8.58	C-Ca-Na-Mg
Vidigueira-Selmes Sector	23	3.24	23	3.68	23	2.52	23	0.04	23	2.22	23	0.49	23	8.71	C-Mg-Ca-Na
Gabbros de Beja	79	3.45	79	3.5	71	1.81	71	0.02	79	1.43	79	0.64	79	9.62	C-Mg-Ca
Charnokites of C. Maior and Elvas	6	3.17	6	3.65	6	0.59	6	0.05	6	1.25	6	0.42	6	10.23	C-Mg-Ca
Pavia-Mora	14	3.27	14	5.1	14	5.19	14	0.09	14	4.81	14	0.35	14	9.87	C-Na-Mg
Low Productivity Sectors															
Amieira-Montalvão Sector	13	0.44	13	0.73	13	0.99	13	0.05	13	0.5	13	0.06	13	2.15	C-Na-Mg
S. Mamede Sector	19	0.86	19	0.63	19	0.48	19	0.03	19	0.43	19	0.09	19	3.41	C-Ca-Mg-Na
Granites of Nisa, P. and S. E. Sector	103	1.12	100	0.86	102	0.96	102	0.07	104	0.86	104	0.15	104	3.5	C-Ca-Na-Mg
Ossa Morena Zone Sector	718	2.75	712	3.08	706	2.3	706	0.06	718	2.91	718	0.35	717	8.05	C-Mg-Ca-Na
South Portuguese Zone Sector	577	2.66	576	4.58	577	6.25	577	0.05	577	8.05	577	0.87	577	6.92	Cl-C-Na-Mg

The hydrochemical analysis shows that the groundwater facies are mainly bicarbonate, except on the South Portuguese Zone Sector, where it is chloride-bicarbonate. This is probably due to the low levels of metamorphism that has affected this area, permitting the presence of salts on the rock matrix of this previous marine environment and to the high concentrations of salts due to the high rates of evapotranspiration that affects this semi-arid environment (Chambel & Almeida 1998). The main cations are the magnesium, calcium and sodium, by this order, having most part of these waters a mixed cation composition between three or two of them.

For the future, the main task will be to conduct aquifer tests in order to have more hydrogeological parameters (transmissivity, permeability, and storage values), and try to understand the relation between instant yields, steady state flow, abstraction and aquifer parameters.

Quantitative and more precise structural studies are necessary to understand the relation between productivity, transmissivity, storage and groundwater pathways, which are mainly defined by the fracture network. Also the weathering layer thickness and type, clearly related with fracture network, are essential to understand and quantify recharge and storage coefficient. Storage and transmissivity which are essential to define groundwater exploration and use in such semi-arid areas as South Portugal.

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