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PRODUCTIVITY AND WATER COST IN FISSURED-AQUIFERS FROM THE IBERIAN CRYSTALLINE BASEMENT (PORTUGAL): HYDROGEOLOGICAL CONSTRAINTS

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RESUMEN

El macizo Hespérico es el mayor fragmento del SW del basamento de Variscan, que ocupa la parte Occidental y Central de la Ibérica. Son discutidos algunos aspectos sobre la Ibérica Central y la zona Galicia-Tras-Os-Montes como la producitividad de sistemas hidrogeológicos basados principalmente en unidades regionales litológicas y morfotectónicas y precipitación. Se propone una relación simple entre transimisividad y capacidad específica de pozos, producción sostenible de los pozos (capacidad a largo plazo) como una función de producción "airlift" y un intento de realizar mapas regionales de transimisividad a partir de información de pozos de baja tecnología. Es presentada una propuesta provisional para estimar el coste de agua subterránea para el suministro público y riego a pequeña escala de la parte septentrional de Portugal.

Palabras clave: rocas cristalinas fisuradas, exploración y explotación de agua subterránea, coste de agua subterránea.

ABSTRACT

The Hesperian massif is the major fragment of SW Variscan basement, which occupies the Western and Central part of Iberia. Some aspects on the Central-Iberian and Galicia-Trás-os-Montes Zones like productivity of hydrogeological systems based on main regional lithological and morphotectonic units and rainfall are discussed. Simple relationships between transmissivity and specific capacity of drilled wells, *sustainable well yield (long-term well capacity) as a function of drilling airlift yield and an attempt to map regional transmissivity from information of low technology water wells are proposed. A tentative approach is presented to estimate groundwater cost for public supply and small-scale irrigation for the Northern Portugal mainland.*

Key Words: *fissured-crystalline rocks, Groundwater exploration and exploitation, Groundwater cost.*

RESUME

Le massif Hesperique est un fragment du socle Varisque qui occupe la partie Occidentale et Centrale de la Péninsule Ibérique. Quelques aspects concernant les Zones Centre-Ibérique et Galice-Trás-Os-Montes, comme la productivité des systèmes hydrogeologiques basée sur les principaux unités lithologiques et morphotectoniques et la précipitation sont discutés. De relations simples entre transmissivité et débit spécifique, débit d'exploitation à long terme et débit 'airlift' sur de puits à faible technologie sont proposées. Un essai de définition du coût de l'eau souterraine pour alimentation en eau potable et utilisation agricole est présenté.

Mots-clé: *roches cristallines fissurés, Prospection et exploitation d'eau souterraine, Coût de l'eau souterraine.*

Introduction

The Variscan Iberian basement represents the best westernmost exposure of the European Variscides (Ribeiro *et al.*, 1990). The human occupation (about four million people living in this region) is quite diversified and includes the mega-conurbation of Porto with concentrated small industrial activities, sparse settlements around the main towns in the northeastern and central inner areas and natural protected areas such as Peneda-Gerês, Montesinho, Estrela and Serra de S. Mamede (North and Central Portugal). Groundwater plays a major role in the economical activities and the quality of life of this population. Public water supply of main towns is nowadays dependent on surface water. However, several hundreds of small villages have subterranean origins. Small-scale agriculture is highly dependent on groundwater resources as well other human economic activities.

This paper is a synthesis of several investigations carried out during the execution of the Basin Master Plans of Lima, Cávado, Ave, Leça and Douro Rivers (*cf.* Hidrorumo, 2000; INAG, undated; Carvalho *et al.*, 2000, 2003). Other hydrogeological and geotectonical aspects are crosscheck after Carvalho (1993), MMA (1998) and Carvalho *et al.* (2004). Some additional aspects are presented, such as productivity of hydrogeological systems based on main regional lithotectonic units and rainfall, the relationships between transmissivity and specific capacity of drilled wells, the sustainable yield (long-term well capacity) as a function of airlift yield when drilling and an attempt to map regional transmissivity from information of low technology water wells. A tentative approach to estimate water cost for public supply and for small-scale irrigation was undertaken.

Geomorphological and geotectonical framework

The so-called Hesperian massif is the major fragment of Variscan basement, which occupies the Western and Central part of Iberia. The northeastern region with a mean altitude of the 700 m of the fundamental surface of the Iberian *'Meseta'* is drained by several major rivers (figure 1). Three main morphotectonic units from basement comprise the study region (Brum Ferreira, 1978, 1980, 1991):

- i) the *"Meseta surface"*, an almost perfect planation surface which in the Portuguese territory stretches both northwards and southwards of the river Douro;
- ii) the *"Central Plateaux"* and the *"Western mountains"* represent several stepped levels instead of a single planation surface.

The Iberian Massif in the Northern Portuguese sector comprises autochthonous and allochthonous metasedimentary sequences imbricated along major thrusts and other tectonic accidents (Ribeiro *et al.*, 1990). The autochthonous litho- and tectono-stratigraphic units are composed by black shales, slates, greywackes, micaschists and quartzites. By turn, the major allochthonous units, in NE Portugal, are characterised by an ophiolite complex sequence nappes comprising serpentinites, flaser gabbros, sheeted dikes and basalts. In addition, the igneous rocks include pre-orogenic and synorogenic suites, which occupie a large exposure of granitoids rocks.

The studied region (figure 2) is located in the Central-Iberian Zone and Galicia-Trás-os-Montes Zone of the Iberian Massif (Ribeiro *et al.*, 1990). Previous regional studies (e.g. Ribeiro, 1974; Brum Ferreira, 1978, 1980; Cabral 1995) pointed out that the most important tectonic megastructures in the Northern Portugal are: i) Régua–Verin and Bragança-Vilariça fault zones (NNE-SSW trend); ii) Porto-Coimbra-Tomar shear zone (NNW-SSE trend); Vigo-Vila Nova de Cerveira–Régua shear zone and Douro-Beira Carboniferous trough (NW-SE trend). Thus, the location of the water wells along the major trending fault zone referred is closely related to several morphotectonical and lithological features (Carvalho, 1993, 1996; Marques *et al.*, 2003; Carvalho *et al.*, 2003).

Hydrogeological investigations: an overview

The main hydrogeological division of the Northern Portugal region is determined by the major active Régua-Verin fault zone (e.g., Freire de Andrade, 1937; Baptista *et al.*, 1998). The mean annual rainfall to the West of this megastructure is over 1 000 mm, reaching 3 000 mm in the National Park of Peneda-Gerês. Towards East and South, aridity conditions take place and a precipitation declines, i.e., a minimum of 500 mm is attained in the Douro river valley, near the Spanish border. These contrasts determine dramatic changes on the recharge conditions. The relative occurrence of metasedimentary rocks is very sparse in the Northwestern area (Figures 1 and 2).

As could be expected, groundwater pathflow is governed mainly by fissured hydraulic conductivity, faulting and weathering, resulting on non-continuous productive zones. The spatial hydraulic connectivity of reservoirs is poor so it is not appropriate to designate these zones, at the scale of regional investigation, as aquifers because there is no flow continuity. It is normal to consider that pathflow is mainly dependent on fracture connectivity. Neverthless, it is clear that in the Variscan Iberian Massif, lithology plays a major role on the productivity of regional geological units and related water wells.

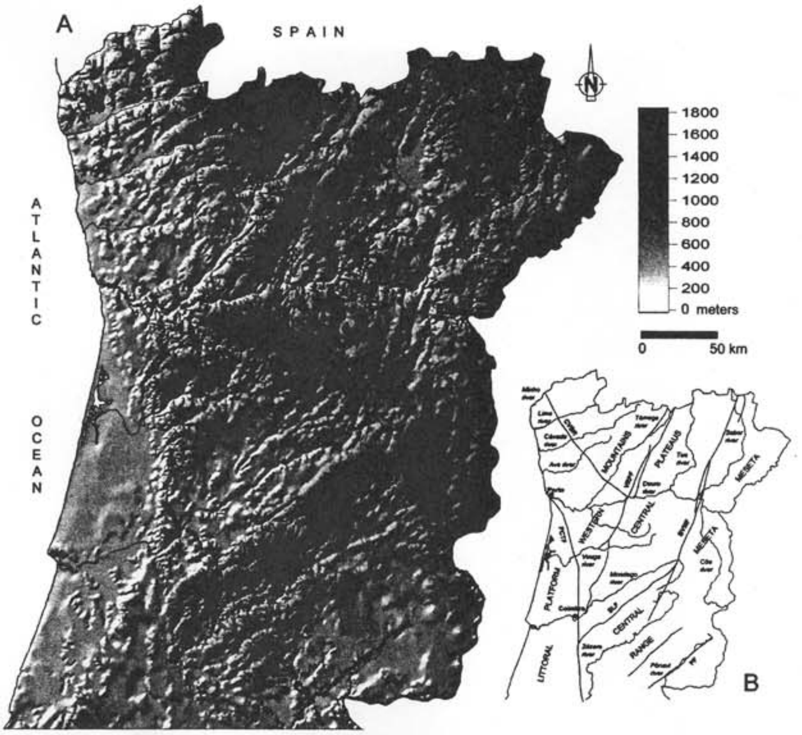


Figure 1. Morphostructural features from Northern Portugal A: Digital elevation model (MDT) of Central and Northern Portugal, based on "Atlas do Ambiente de Portugal" (1/1000000); B: Main rivers and regional morphotectonic units; major faults: PCTF – Porto-Coimbra-Tomar strike-slip shear zone; CVBR – Vigo-Vila Nova de Cerveira-Régua fault zone; VRPF – Verin-Régua-Penacova fault zone; BVMF – Bragança-Vilariça-Manteigas fault zone; SLF – Seia-Lousã fault zone; PF – Pônsul fault

Recharge and resources

Moitinho de Almeida (1970), Paradela (1984) and Gonçalves Henriques (1985) first attempted the evaluation of groundwater resources at a regional level. They suggested regional resources of about 50 m^3/dia/km^2, i.e., less than 0,6 l/s/km^2. Other authors such as Alencoão (1998), M. R. Pereira (1999), Pedrosa (1999), A. Oliveira & Ferreira (2000), Lima (2001), Afonso (2003), and ERHSA (2003), used several hydrometeorological methods to access infiltration. The results are generally expressed in terms of Infiltration Coefficient, (I/P) x 100 (I: infiltration, P: Annual Precipitation), and exhibits dispersion in a range of 1-30%. Recently, Carvalho *et al.* (2000) combining river hydrograph analysis using the Castany-Berkallof method and groundwater balance in controlled local basins (exploited in the bottling water industry) suggested the consideration of a generalized Infiltration Coefficient of about 17%. However, the Temez model for these areas (Hidrorumo, 2000; INAG, undated) delivers coefficients of infiltration of only 6%. Those parameters allow the evaluation of sustained average "aquifer productivity" from 80 to 255 m^3/dia/km^2 (1-3 l/s/km^2), considering the existing mean annual rainfall and the average 17% Infiltration Coefficient, slightly sub-evaluated when compared to Pedrosa *et al.* (1999) proposal.

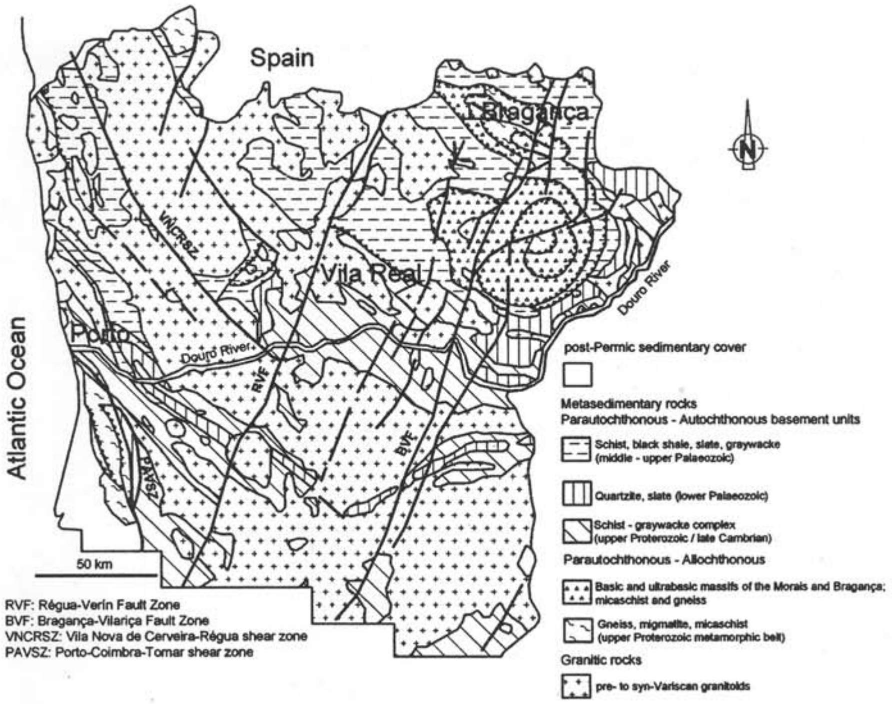


Figure 2. Geological framework from Northern Portugal (very simplified and adapted after Oliveira et al., 1992)

Productivity of wells

The studied region is currently stage for intensive, uncontrolled groundwater exploitation by *circa* two hundred down-the-hole-hammer drilling rigs, mainly operated by small family sized companies. Depth of drilling is generally till 100-150 m, but exploration up to 300 m deep is known in a few particular projects. Carvalho *et al.* (2004) studied yields and transmissivities, which were obtained considering an equivalent porous media over 250 wells and concluded that the main lithologie's distribution of median long-term well capacity on the Portuguese Variscan Massif is as follows:

- (i) Metasediments excluding quartzitic rocks : 0,5 l/s;
- (ii) Quartzitic rocks: 0,7 l/s;
- (iii) Granitic rocks: 0,1 l/s and
- (iv) Contact rocks: 0,3 l/s.

Two families of wells were studied in this work (figure 3):

- (i) 110 wells located at the Viseu and Porto areas, and,
- (ii) 170 wells in Trás-os-Montes region.

All the wells were located, drilled, completed and tested by ACavaco, Lda., Portuguese exploitation and drilling company, thus being a remarkable homogeneous representative data. The wells were drilled with

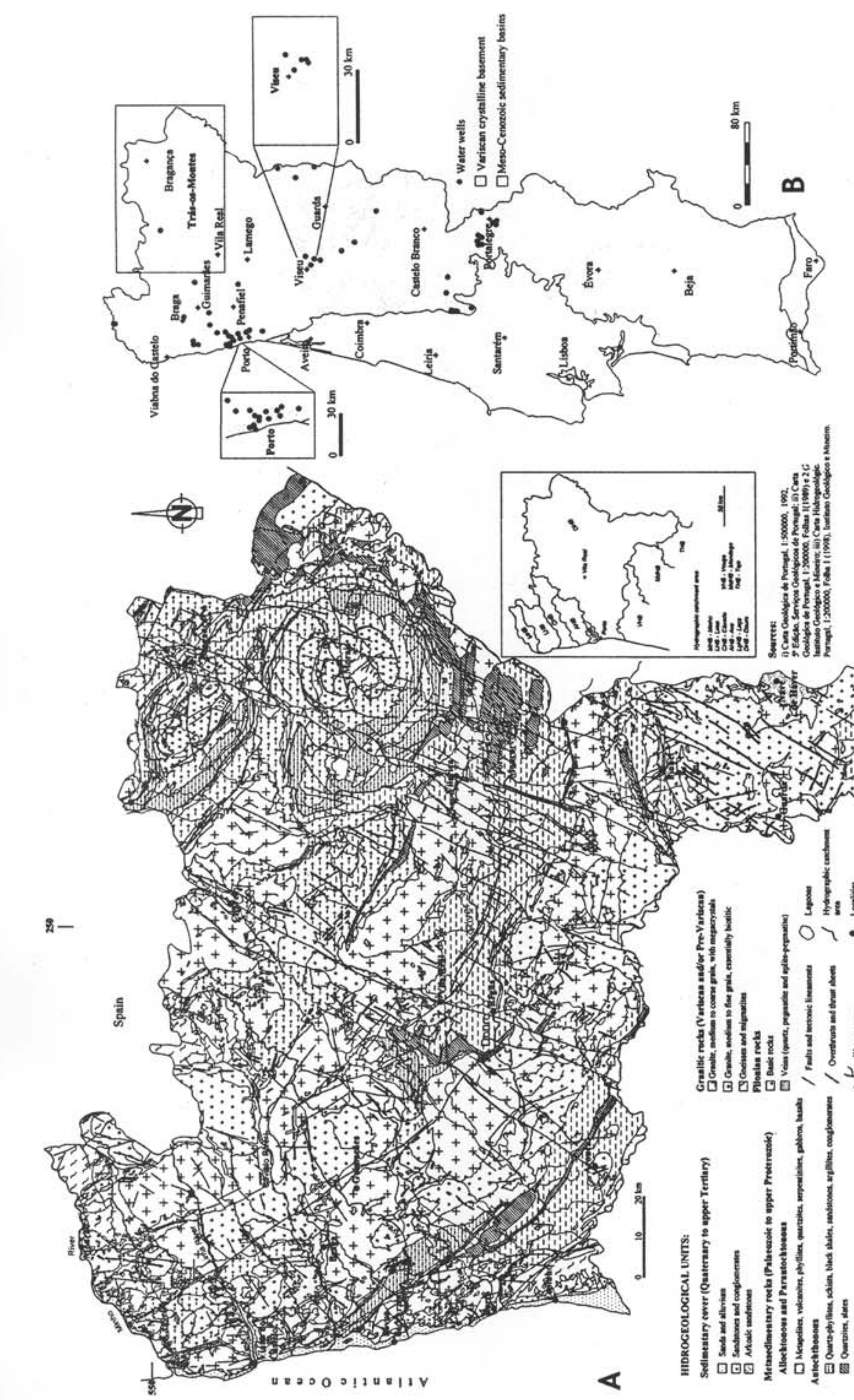


Figure 3. Hydrogeological outline from Northern Portugal; A – Regional hydrogeological units (adapted from Carvalho et al., 2003); B – Studied water wells (see table 2 for groundwater characterisation)

down-the-hole hammer rigs. Average design of wells included drilling with ø 81/2" and 61/2" and steel and PVC casing up to ø 140 mm. Screens are generally of the non-continuous slotted pipe type with an open area of about 10% which is sufficient to reduce to a tolerable level the head losses in the well. The Table 1 summarises productivity of wells and transmissivity for both areas of the Central-Iberian Zone (*s.l.*). The agreement between the two sets of wells is highly coherent. Long-term well capacity and transmissivity are clearly dependent on lithology, being metasediments the higher transmissive and productive unit. Geological structures, quartz veins and fault gouge are significant indicators of increased transmissivity as stated by Hidroprojecto *et al.* (1987, 1988, 1989) and M. R. Pereira (1992, 1999). For the entire Central-Iberian Zone (*s.l.*) the median long-term well capacity is 0,42 l/s including productive and non-productive wells. The median transmissivity is 2,3 m^2/day. The existing long-term well capacity is similar to those occurring in other world regions (*e.g.* Larsson, 1987; Lloyd, 1999; Stober, 2000; Carvalho & Chaminé, 2002; ERHSA, 2003). These evidences supported also by Alencoão (1998), Mendonça *et al.* (1999), M. R. Pereira & Almeida (1997) and Lima (2001), justify the hydrogeological map presented in the figure 3.

Selected Areas	Lithology	Long-term well capacity (l/s)		Transmissivity (m^2/day)	
		Median	Maximum	Median	Maximum
Porto and Viseu Areas	Metasediments (excluding quartzitic rocks)	0,50	3,5	4	59
	Quartzitic rocks	0,70	1,4	-	-
	Granitic rocks	0,04	3,5	3,0	54
Trás-os-Montes Region	Metasediments (excluding quartzitic rocks)	0,50	3,0	2,3	63
	Quartzitic rocks	0,78	3,0	4,0	32
	Granitic rocks	0,00	2,0	0,3	148

Table 1. Distribution of yields and transmissivities on crystalline aquifers of the main lithologies of the Central-Iberian Zone (s.l.). [Long-term well capacity: the sustainable exploitation capacity determined by pumping tests, considering the constraints defined by Carvalho (2000) and Carvalho et al. (2004) and a continuous pumping period of 180 days. A common misunderstanding is the assumption of the long-term well capacity as the airlift yield defined when drilling or when developing the well]

Specific capacity of wells and transmissivity

In this investigation, straightforward relationships between specific capacity of wells and transmissivity, considering an equivalent porous media, were developed. The pumping tests had a minimum duration of 6 hours at a constant rate. No step-drawdown tests were available. Theis method and the Cooper-Jacob logarithmic approximation of the Theis equation were applied. Recovery data were interpreted by the Theis Recovery method. Results from the transmissivity computation show the following features:

- (i) Theis method generally gives values about 0,5 to 1,0% higher than with the Cooper-Jacob approximation, the determination of regression coefficient (R^2) being 0,7 and
- (ii) transmissivity derived from Theis recovery method is lower that the resulting from Theis method with the relation T (recupTheis)=0,72 T (Theis) with R^2=0,73. In a few sites, observation wells were present, being feasible to determine the storage coefficient (S). Values of about 10^{-4} were computed; suggesting that water flow for these wells is done under confined or semi-confined conditions.

The specific capacity of a well is defined as the ratio of discharge to drawdown (Q/s) at the pumping well for a given time and it has dimensions [L^2T^{-1}], the same as transmissivity. The solved Thiem equation for transmissivity showed that transmissivity should be related to specific capacity with a constant C with the form T= C (Q/s). However, Thiem equation assumes a well 100% efficient, which is not the case in field practice, where turbulent head loses increase drawdown in the production well. By this reason, simple transmissivity *vs.* specific capacity (Q/s) relationships tends to underpredict transmissivity. The value for C varies from 0,9 to 1,5. Custódio & Llamas (1983) suggest C = 0,74 to 2,1 for non-confined aquifers and 0,54 to 1,04 for confined conditions. Considering the Central-Iberian Zone (*s.l.*) it was found a coefficient C of 0,72 with a regression coefficient (R^2) of 0,97 for six representative wells, during six hours of continuous extraction as shown in figure 4. This value is in the range of confined aquifers according to Custódio & Llamas (1983). Several similar expressions were deducted by Carvalho *et al.* (2004) for the entire Portuguese Variscan basement.

The absence of step-drawdown tests did not allowing the computation of turbulent head losses, so the corresponding evaluated transmissivities with this approach is probably underpredicted as mentioned above. The specific capacity decreases with pumping time (t). In order to evaluate the evolution of parameter C for different pumping times we have plotted the average C=T/(Q/s) *vs.* pumping time for eight investigated areas. As shown in figure 4 we found the logarithmic relation C=0,1579 Ln (t)+0,5382 with a regression coefficient (R^2) of 0,97, allowing the estimation of the transmissivity for several pumping times in the Central-Iberian Zone (*s.l.*). For a given well the specific capacity also decreases with the pumping rate as a result of the increasing importance of well and formation losses. In the case of this investigation, we consider the pumping rate influence in the specific capacity as negligible because design of wells is conform with the best practices (Carvalho, 2000) and pumping tests are adjusted in order to be representative of long-term well capacity.

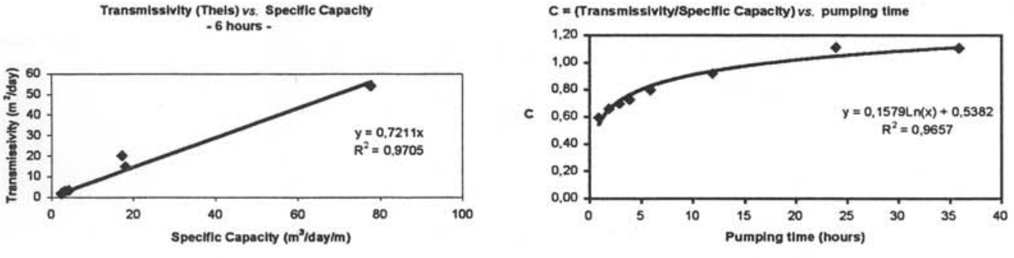


Figure 4. Transmissivity (Theis) vs. Specific Capacity; C=T/(Q/s) vs. pumping timefor several investigated areas

Evaluation of long-term well capacity

Productivity of wells is probably the most important factor for designers and well owners at a local level. Confusion with productivity of the aquifers, former concern for land-use planers and for management purposes, must be avoided. In this section, we will focus on airlift discharge (when drilling or developing) and long-term well capacity, common source of misunderstandings and seasonal overexploitation problems. When drilling with down-the-hole air percussion method the instantaneous water production can be evaluated with a relative accuracy. This airlift yield is the result of the submergence inside the well, and (the dynamic level being unknown) does not represent the long-term well capacity. A common misunderstanding is the assumption of the long-term well capacity as the airlift yield defined when drilling or when developing the well. Main constraints for the evaluation of the long-term well capacity considering Carvalho (2000) and Carvalho *et al.* (2004) are the available drawdown and the drawdown during the pumping test extrapolated to 180 days. Generally, in these "aquifers" at a constant pumping rate, drawdown in wells plotted against time (on semi-log graph) forms a straight line. This line, if pumping test is well managed, in the latter pumping time period is representative of the pseudo-stabilization of drawdown and can be extrapolated. We plotted in figure 5 long-term well capacities assumed for the entire population of studied wells. A Coefficient of Reduced Capacity (CRC = long-term well capacity/airlift yield) of 0,28 with $R^2=0,5$ was found. The strong dispersion recommend caution when using this relationship. However, in the Central-Iberian Zone (*s.l.*) according to this approach the long-term well capacity would be *ca.* 1/3 to 1/4 of the airlift yield when drilling or developing.

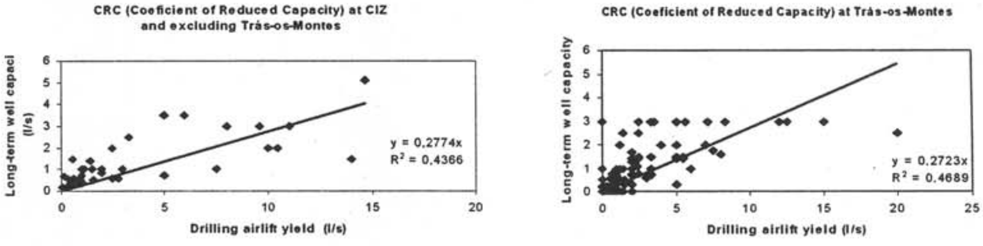


Figure 5. Coefficient of Reduced Capacity vs. Drilling airlift yield for the studied areas

The Meter-Capacity Index (MCI)

A common problem in this type of hydrogeological environment is the assessment of well productivities at a regional level. The inexistence of a continuous regional flow and the low quality of the hydrogeological information obtained from local drillers justifies an approach based in the low cost information, that is generally available.

Carvalho (1993) proposed the use of the Meters Capacity Index (MCI) defined, for a given area as:

$$\text{MCI} = \Sigma \text{ total drilled metres} / \Sigma \text{ total yield (l/s) in wells with long-term well capacities} > 0{,}5 \text{ l/s}$$

This MCI allows the evaluation of the geological risk (failure rate) and the computation of water cost including the geological risk as stated in figure 6. The previous presented form of MCI must be considered as an *adjusted* MCI, because the computed yields are the long-term well capacities. Indicative values for the MCI are:

- (i) metasediments excluding quartzitic rocks: 40-120 m/l/s;
- (ii) quartzitic rocks: 40-80 m/l/s, and
- (iii) granitoids: >120 m/l/s.

In this investigation we explored the possibilities to access the regional median transmissivities using the *adjusted* MCI and a new *Gross* MCI. The *Gross* MCI is defined as:

*Gross*MCI = Σ total drilled metres / Σ total air lift yield (l/s) in all wells

The ratio T/(1/MCI) is dimensionless, because dimensions are the same [L^2T^{-1}]. For 14 selected representative areas in Trás-os-Montes (Figures 6 and 7) a linear regression model analysis allows the assumption of single relationships with strong correlation, as follows:

- (i) Median transmissivity equalizes approximately (1/*Gross*MCI), and
- (ii) Transmissivity ≈ 3∗(1/*Adjusted* MCI).

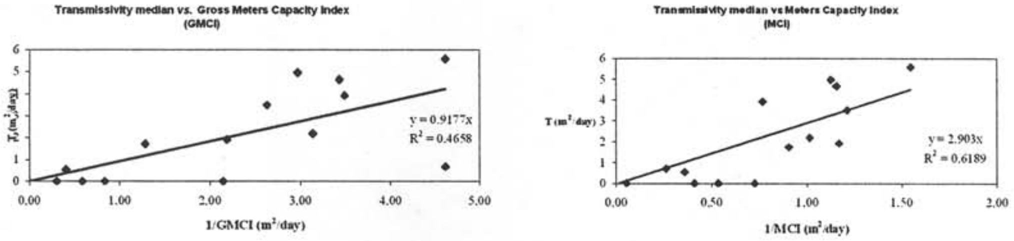


Figure 6. Transmissivity median vs. GrossMCI and Transmissivity median vs. MCI

Other similar equations can be deducted for the mean transmissivity.

Carvalho (1993) presented a proposal for evaluation of water cost for small-scale irrigation in Trás-os-Montes, based on the *adjusted*MCI. An actualised version of this approach comprising cost to cover exploration uncertainties, drilling, pumping installation and auxiliary surface equipment is presented here. The average installation cost for an equiped water well able to irrigate 1hectare, in a sector with MCI comprised between 80 and 120 m/l/s is € 7 000.

The groundwater cost for public supply in the studied area was evaluated considering:

- (i) investment costs in exploration and construction of wells, pumping equipment and water treatment,
- (ii) exploitation costs: electricity, maintenance, technical assistance and bacteriological and chemical control.

Three categories according to the adjusted MCI were considered, the mean cost for lithologies with MCI comprised between 80 and 120 m/l/s, being € 0,22/m^3 (Table 2 and Figure 3).

	Long-term well capacity and water cost for public supply										
	More suitable exploitation structures		Geological risk of failure (MCI*, m/l/s)			long-term well capacity (l/s)**			treated water cost (€/m^3)		
Lithological Units	excavated wells, galleries and springs	drilled wells	very-high MCI>120	high 80<MCI<120	low MCI<80	very-low Q< 1l/s	low 1<Q<2	high Q>2	high to very-high m^3>0.24	medium 0.21<m^3<0.24	low to very-low m^3<0.21
Sedimentary cover, generally unconsolidated: alluvium; sand	x$^{1)}$				x		x	x$^{2)}$			x
Sedimentary cover, generally detritical, less consolidated: sandstones and conglomerates	x				x		x				x
Sedimentary cover, generally detritical, consolidated: arkosic sandstones		x			x		x				x
Metapelites, vulcanites, phyllites, quartzites		x		x			x			x	
Quartz-phyllites, schists, black shales, sandstones, argillites, conglomerates		x		x	x		x			x	x
Quartzites, slates		x		x	x		x			x	x
Schists, graywackes, metaconglomerates Migmatites and gneisses		x	x	x	x	x	x		x	x	x
Granite medium to coarse grain, with megacrystals	x		x	x		x			x	x	
Granite medium to fine grain, essentially biotitic	x		x	x		x			x	x	
Gneisses and migmatites	x		x			x			x		
Ophiolite complex nappes: serpentinites, flaser gabbros, sheeted dikes and basalts		x	x	x		x			x	x	
Veins (quartz, pegmatite, aplite-pegmatite)		x			x		x				x

$^{1)}$ except in the Chaves Valley where drilled wells are the most productive; $^{2)}$ only in the Chaves Valley;
* MCI [Meters Capacity Index] in a given area, total drilled meters in one or several wells to obtain 1l/s; ** median long-term well capacity

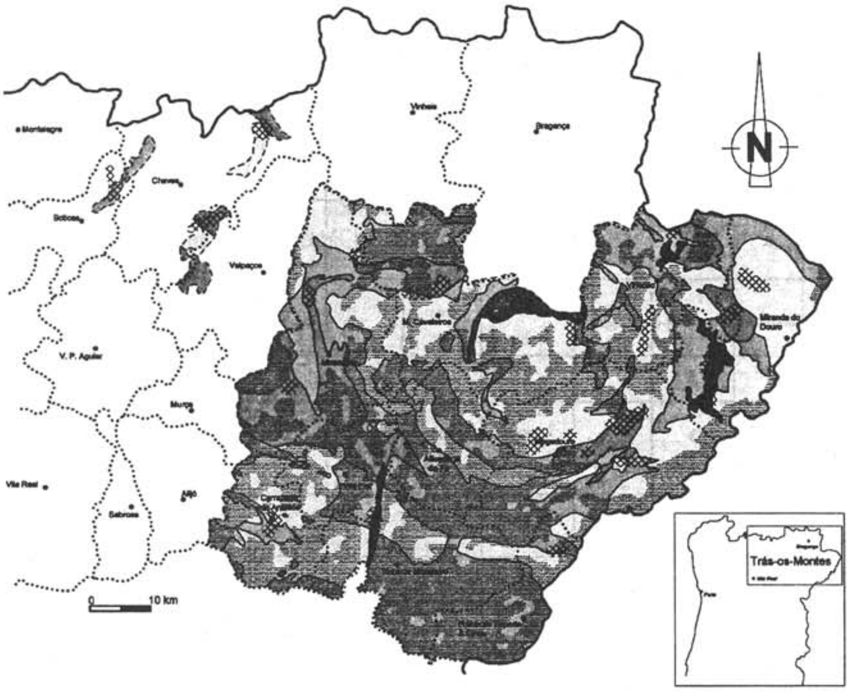
Table 2 – Groundwater supply for public purposes in Northern Portuguese Variscan basement (see Figure 3)

Conclusions

The investigations carried out allowed the assumption of single relationships based on lithology and available information on representative wells and pumping tests. Relations such as:

- (i) transmissivity *vs.* specific capacity for different pumping times,
- (ii) Coeficient of Reduced Capacity (CRC) between long-term well capacity and airlift yield when drilling or develloping, and
- (iii) *adjusted* and *gross* MCI (Meters Capacity Index) are powerfull tools to regionalize median or mean transmissivities and water costs.

However, caution must be taken when using these approaches at a local level, or as predictive tools, as hydrogeomorphological, geotectonical and hydrological constraints can considerably modify the deduced conditions. In conclusion, the effects of geological heterogeneity of rock-masses and scale are significant issues in hydrological, hydrogeological and hydro-engineering studies and projects.



GROUNDWATER POTENTIAL FOR SMALL-SCALE IRRIGATION IN TRÁS OS MONTES

Fissured rocks (metasediments, granite, quartzite, metavolcanics, basic and ultrabasic rocks.

Class I: Slope >100m/km. Poor conditions for small-scale irrigation at a regional level

Sub-Classes	Ground water potential
■ I.1	In gentle slopes and intramontane valleys consider geological risk as defined for Class II
■ I.2	
■ I.3	
■ I.4	

Class II: Slope<100m/km. Suitable conditions for small-scale irrigation at a regional level

Sub-Classes	Adjusted MCI (m/l/s) (I)	Geological Risk (Failure risk)	Water cost (€) (II)	Groundwater Potential
■ II.1	< 40	Very Small	< 4000	Favourable areas
▨ II.2	40 - 80	Small	4000 - 6000	
▨ II.3	80 - 120	Moderate	6000 - 8000	
□ II.4	> 120	High	> 8000	Unfavourable areas
■ II.5	Small sedimentary cover.			Favourable areas

Porous rocks (sand, clay and gravel)

(I) Adjusted MCI (Meters Capacity Index) = $\frac{\Sigma \text{ total drilled meters in all wells (m)}}{\Sigma \text{ total yield (l/s) in wells with long-term capacity higher than 0,5 l/s}}$

(II) Investment to obtain 1 l/s (construction of wells and pumping equipment)

········ Administrative Boundary

- - - - Representative area limit

XXXXX Representative area

Figure 7 – Groundwater potential for small-scale irrigation in Trás-os-Montes (see also figure 3 and compare with Table 2).

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