ASSESSING AND MODELLING HARD ROCK AQUIFER RECHARGE BASED ON COMPLEMENTARY METHODOLOGIES - A CASE STUDY IN THE "GABBROS OF BEJA" AQUIFER SYSTEM (SOUTH PORTUGAL)

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ABSTRACT

The "Gabbros of Beja" Aquifer System extends for approximately 350 km^2 and is one of the most important reservoirs of groundwater in the context of hard rocks aquifers of South Portugal (Alentejo Region). The average annual rainfall in the area is about 500 to 600 mm.
Groundwater resources are used for public supply over 3 municipalities and irrigation. During drought cycles consumption increases and pumping rates decrease with correspondent management difficulties and conflicts between private and public interests.
The correct assessment of annual recharge is of utmost importance for regional planning and management of groundwater resources under semiarid climate conditions. Moreover the aquifer was recently declared vulnerable to nitrate diffuse pollution of agriculture origin and recharge mechanisms are the major natural factor controlling contamination of shallow waters in the "Gabbros of Beja" aquifer.
Recharge assessment and modelling was performed on the base of several complementary methodologies: 1) water balance based on historical data of annual pumping rates; 2) chloride mass balance between groundwater and rainfall compositions; 3) daily sequential water balance modelling of hydrological parameters using Balseq model, and 4) soil and vadose zone daily water balance modelling using lumped model Earth and piezometric water level curves for calibration.
Results of direct and indirect methods show that annual average recharge should be between 10% and 20% or even more of annual rainfall.

Key-words: recharge modelling; water balance; chloride mass balance; piezometric curves; Gabbros of Beja Aquifer System

1. INTRODUCTION

Research is based on funding project "Assessing the impacts of agriculture on groundwater quality using nitrogen isotopes", in progress in the rural region of Beja (south Portugal), under semiarid conditions for the period 2004-2007. National Research Authority (Science and Technology Foundation - FCT) supports the project.

This paper will focus on *Assessing and Modelling Aquifer Recharge in the "Gabbros of Beja" Aquifer System* (350 km^2). The Aquifer represents the most productive hard rock aquifer in the region (Alentejo, south Portugal) and the best agriculture land with direct consequences regarding nitrate diffuse pollution (Paralta *et al. 2005a*). Municipality public supply depends on groundwater pumping during summer and cyclical droughts.
Study area is located in South Portugal between Ferreira do Alentejo (west) and Serpa (east) (Figure 1), covering an area of 350 km^2 in Ossa-Morena geotectonic unit. The average annual rainfall in the area is about 500 mm in Serpa to almost 600 mm in Ferreira do Alentejo.

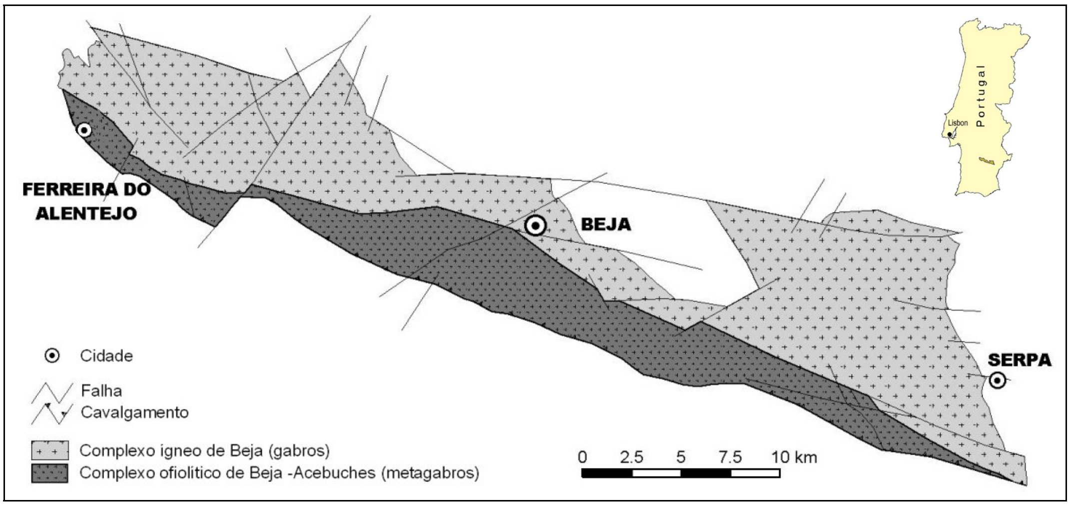


Figure 1– Geographical location and schematic geology of the"Gabbros of Beja"Aquifer System.

Recharge can be defined as the amount of water added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration by direct vertical percolation through the vadose zone.
The gabbro-dioritic shallow aquifer was recently declared vulnerable to nitrate non-point diffuse pollution in the context of official publication of "Gabbros of Beja" Vulnerable Region (Portaria 1100/2004, September 3).

The second fertilization period for cereals crops is coincident with the major recharge period between January and March/April, increasing aquifer vulnerability to agriculture nitrogenous products (Paralta *et al.* 2005b).
First approach in recharge assessment depends on data available about climate, hydrological and geomorphologic information, geology and land use to estimate critical parameters for water balance such as evapotranspiration.
Interpretation of hydrogeological features are important in selection of appropriate methodologies based in tracer techniques, piezometric fluctuations or saturated flow models based in Darcy`s law.
Methods of recharge assessment and modelling can be classified into two distinct groups (Van der Lee & Gehrels 1990):

I) Direct methods
- Water balance studies (empirical balance studies);
- Physical balance studies (groundwater and surface water);
- Unsaturated zone models (describing recharge mechanisms above the groundwater table deterministically);
- Tracer techniques (chemical, bacteriological and isotopes).

II) Indirect methods (saturated zone)
- Piezometric fluctuation (relationship between groundwater table and recharge);
- Darcy´s Law and physical models of saturated flow.

The direct methods describe recharge mechanisms as percolation, soil moisture distribution, evapotranspiration, etc, to estimate recharge, approaching from the top/ground.
The indirect methods use fluctuations of groundwater table as indicator of the amount of actual recharge knowing basic hydrologic parameters such as hydraulic conductivity (K), storage coefficient (STo), recession constant (RC), etc.
Recent development in microwaves remote sensing techniques made it possible to estimate surface soil moisture that can be used to assess and estimate groundwater recharge (Gouweleeuw 2000, Jackson 2002).
Regarding recharge in the "Gabbros of Beja Aquifer System" several authors indicated different ratios such as 30% (Oliveira *et al.* 1994), 4% (Duque 1997) and 14% (Duque 2005) without specific recharge studies.
Other authors (Paralta 2001, Paralta *et al.* 2003) made specific recharge studies based on several complementary methodologies: (1) water balance based on historical data of annual pumping rates; (2) chloride mass balance between groundwater and rainfall compositions; (3) daily sequential water balance modelling of hydrological parameters

using Balseq model and (4) soil and vadose zone daily water balance modelling using lumped model Earth and piezometric curves for calibration.
Results of direct and indirect methods showed that annual average recharge should be between 10% and 20% of annual rainfall and sometimes even more.
Additional information on the "Gabbros of Beja Aquifer System" and related agro-environmental problems can be found in academic thesis (Duque 1997; 2005 and Paralta 2001) and papers (Paralta & Francés 2000; Paralta & Ribeiro 2000; Paralta & Ribeiro 2001; Paralta & Ribeiro 2003).

2. RECHARGE ASSESSMENT METHODS

Various techniques are reported in bibliography to quantify groundwater recharge. This paper presents four different but complementary methods for critical analyses and comparison.

1. Environmental tracers – chloride (Scanlon *et al.,*2002)
2. Daily sequential water balance – EARTH model (Van der Lee & Gehrels 1990)
3. Daily sequential water balance – BALSEQ model (Lobo Ferreira 1981)
4. Annual water balance (pumping rates)

The methodologies and techniques proposed may be obtained through the bibliography. The critical analysis of the methods, with the necessary rigour, would occupy space that isn't available in the format of this paper.

2.1 Environmental Tracers – Chloride

Environmental tracers such as chloride (Cl) are produced naturally in the Earth`s atmosphere and can be used to estimate recharge rates (Scanlon *et al.* 2002).
Chloride concentrations generally increase through the root zone as a result of evapotranspiration and remain constant below this depth. Deep drainage is inversely related to Cl concentration in the unsaturated-zone pore water. This inverse relationship results in the Cl mass balance (Eq. 1).

$$R = D / P \cong C_p / C_g \qquad \text{[Eq. 1]}$$

R – groundwater recharge
D – deep drainage (mm)
P – annual rainfall (mm)
Cp – Chloride concentration in rainfall
Cg – Chloride concentration in groundwater

Considering chloride as conservative ion and that no natural or anthropogenic sources of chloride are present in the area, groundwater recharge (R) can be estimated from chloride mass balance between rainfall and groundwater.

2.2 Daily Water Balance – EARTH model

EARTH is a lumped parameter hydrologic model for the simulation of recharge and deep groundwater level fluctuations. Van der Lee, Gehrels and Gieske developed the model in 1989 for use in the GRES project (Groundwater Recharge Evaluation Study).

The EARTH model can be applied in different agro-hydro-meteorological scenarios to assess and model water balance namely:

- precipitation excess;
- pounding and surface runoff;
- soil moisture content and transport in the unsaturated zone;
- actual evapotranspiration;
- aquifer recharge;
- groundwater table fluctuations.

EARTH model has been applied to semi-arid climatic conditions under different scenarios successfully.

The model is a combination of direct methods and indirect methods. The first three modules, MAXIL, SOMOS and LINRES, are the "direct" part of the model, calibrated with the measured time series of soil moisture. SATFLOW is the indirect part of the model and calculates the groundwater level with the estimated recharge of the direct part. The SUST model calculates surface runoff (Figure 2).

The following paragraphs describe briefly major aspects of each module and mathematical outlines for SATFLOW model. For more information see Van der Lee & Gehrels (1990).

- MAXIL (MAXimum Interception Loss) – estimate surface retention (water remaining at the surface);
- SOMOS (SOil MOisture Storage) – calculates the mass balance between actual evapotranspiration, percolation, ponding and/or runoff. The remaining part is the change in soil moisture;
- SUST (SUrface STorage) – calculates pounding and runoff;
- LINRES (LInear REServoir routing) – redistributes percolation in time for the unsaturated hard rock or the soil beneath the root zone;
- SATFLOW (SATurated FLOW model) – simple one-dimensional parametric groundwater model. Uses recharge estimation from LINRES model to calculate groundwater level knowing storage coefficient and recession coefficient.

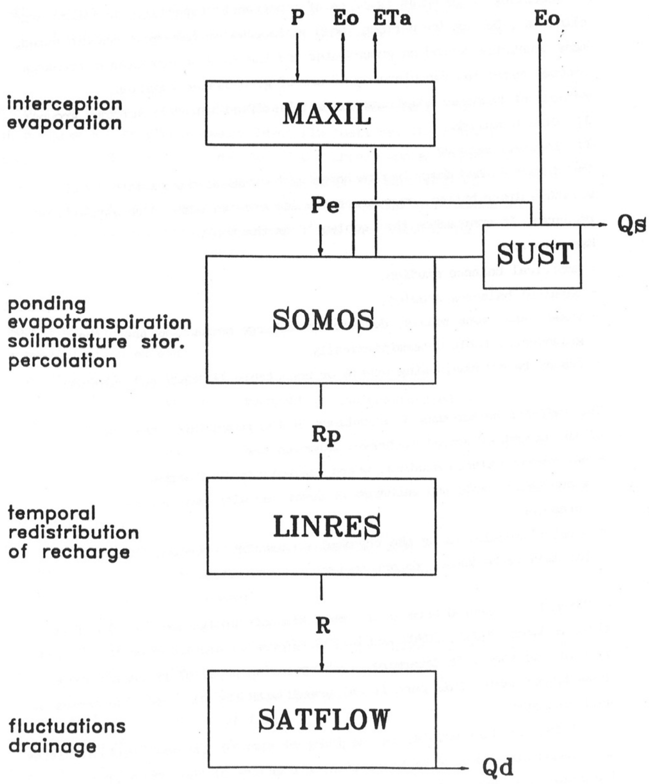


Figure 2 – Flow chart of EARTH (Van der Lee & Gehrels 1990).

SATFLOW model can be used as a simple independent one-dimensional parametric model using *input* from previous models. Mathematical explanation for groundwater level fluctuations can be described as follows (Van der Lee & Gehrels 1990):

$$h = RC \frac{R}{STo} - RC \cdot (h') \qquad \text{[Eq. 2]}$$

h – groundwater level [L]
h′– derivative of h [$L.T^{-1}$]
RC – recession constant [T]
R – recharge [$L.T^{-1}$]
STo – storage coefficient

This equation is a linear transfer function that can be solved numerically:

$$h_t = h_{t-1} - \frac{TS}{RC} h_k + TS \frac{R}{STo} \qquad \text{[Eq. 3]}$$

k = time index
TS – time step
explicit (backward): k = t-1
implicit (forward): k = t

Equation [3] was tested as an independent model in the Netherlands with fairly good results. The model uses the implicit solution (Van der Lee & Gehrels 1990).
Input parameters were obtained trough the bibliography and recent field work with the support of International Institute for Aerospace Survey and Earth Sciences (ITC) professors and students, namely Professor Macieck Lubczynski and Dr. Rafael Cortez.
Daily potencial evapotranspiration was calculated by FAO Penman-Monteith method (Allen *et al.* 1998) for the period of 2001-2003.

2.3 Daily Sequential Water Balance – BALSEQ Model

The BALSEQ model (Lobo Ferreira 1981) is a numerical model for daily sequential water balance at soil level, developed in 1981 by Lobo Ferreira to estimate groundwater recharge in Porto Santo island (Portugal). The flowchart of this model is presented in Figure 3. The model has been applied several times at national (Portuguese) scale (e.g. in Porto Santo island (Lobo Ferreira *et al*. 1981), or Setúbal peninsula (Oliveira *et al.* 1994), and at international level [e.g. in India, in Bardez taluka, Goa state (Chachadi *et al*. 2001) or in Kakinada (Chachadi *et al.* 2002)]. A short description of the method's fundamentals is presented:
For the conceptual case of an area where there is no artificial recharge, no surface flow entering the area, and the groundwater level is always below the root depth, the water balance equation for the soil of that area can be expressed by:

$$P - RET - \Delta A_l - Sr - Dp = \varepsilon \qquad \text{[Eq. 4]}$$

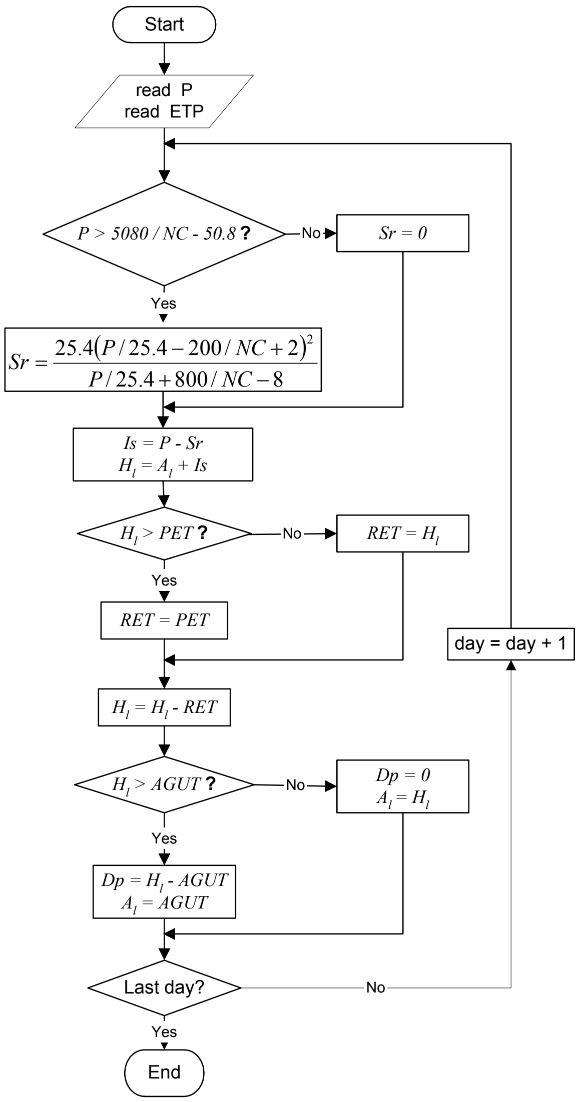
where P is the precipitation, RET is the effective evapotranspiration, ΔA_l is the variation (*final* - *initial*) of the water stored in the soil, Sr is surface runoff, Dp is deep percolation and ε is the calculation error of the balance.
The sequential mass balance approach intends to measure or estimate and compute the P, RET, Sr and ΔA_l parameters, computing Dp by solving [Equation 4] considering $\varepsilon = 0$.
Recharge (R) is then assumed to be equal to Dp:

$$R = Dp = P - RET - \Delta A_l - Sr \qquad \text{[Eq. 5]}$$

For the sequential application of that expression, it is necessary to know the values of P and of the potential evapotranspiration (PET) referred to each time interval, as well as of the value of maximum water reserve in the soil that can be used by plants ($AGUT$):

$$AGUT = (s_r - w_p) \,.\, r_p \qquad \text{[Eq. 6]}$$

in which s_r is the specific retention, w_p is wilting point and r_p is the depth of the plant roots. A runoff curve number (NC), that depends on soil permeability and on land use, is used in the process of estimating surface runoff. NC values vary between 0 (it corresponds to the area with very high permeability, where all water infiltrates into the soil), and 100 (that corresponds to a completely impermeable zone). Figure 3 presents the formula to compute surface runoff, as a function of P and NC.



P = precipitation
PET = potential evapotranspiration
NC = runoff curve number
Sr = surface runoff
Is = surface infiltration
$\boldsymbol{A_l}$ = water stored in the soil in the end of the day
$\boldsymbol{H_l}$ = water stored in the soil along the day
RET = evapotranspiration
AGUT = maximum amount of water available for evapotranspiration
Dp = deep percolation

Figure 3 – Flow chart of BALSEQ model (created after Lobo Ferreira 1981).

For the characterisation of the soil type, four classes are considered (A to D):
Type A soils present low direct runoff potential and high infiltration capacity, even when completely wet. This class includes mainly deep sands with good to excessive drainage. They present high permeability.
Type B soils present direct runoff potential below the average and moderate infiltration capacity, when completely wet. They include mainly more or less deep soils, with moderately thin to moderately coarse texture and more or less drained. These soils present intermediate permeability.
Type C soils present direct runoff potential above the average and low infiltration capacity when completely wet. They include mainly soils with underlying impermeable layers, and soils with moderately thin texture. These soils present low permeability.
Type D soils present high direct runoff potential and very low infiltration capacity when completely wet. They include mainly expansible clayey soils, soils with phreatic level permanently close to the surface and soils with low depth impermeable bedrock. These soils present very low permeability.
Oliveira *et al.* (1997) characterised soils in the classes A to D, based on the soils descriptions represented in the soil map of Portugal at 1:50,000 scale. Using the same descriptions, the same authors caracterised s_r and w_p parameters, used for *AGUT* computation.
Based on *Corine Land Cover* map and on the tables of the United States Soil Conservation Service, Vermeulen *et al.* (1993) presented a table to describe parameter *NC* as a function of this map legend and of soil type (A to D). Also, based on *Corine Land Cover* map, the same authors presented approximated values of soil depth for evapotranspiration (r_p).
The daily soil water balance method is a good method to forecast differences on total recharge in response to changing daily precipitation pattern. Moreover, as a general characteristic of the method it allows the determination of seasonal recharge. However, it must be considered that the presented method provides a value of the water available for deep percolation, and that this deep percolation will take some time to reach the aquifer.
The parameters s_r, w_p, r_p and soil type, defined on the basis of the referred tables as a function of the existing soils and on land cover in the study area, present the values shown in Table 1. Land cover are cereal crops (wheat).

Table 1 – Characterization of s_r, w_p, r_p, soil type ad AGUT.

Soil	s_r (-)	w_p (-)	r_p (mm)	*AGUT*	Soil type
Bp	0,307	0,140	500 - 600	83 -100	D
Bpc	0,398	0,195		101 - 122	D
Cp	0,415	0,204		105 -127	D

2.4 Annual Water Balance (pumping rates)

Considering long term pumping rates in Pisões catchment (20 km^2), exploitation is a good estimation of recharge. Data available from municipality wells offers means to estimate groundwater recharge, namely after durable droughts.

3. RESULTS AND DISCUSSION

3.1 Environmental Tracers – Chloride

Chloride mass balance used a total of 155 data of chloride concentrations in groundwater of the "Gabbros of Beja" aquifer from Duque (1997), Paralta (2001) and Serra (2002), representing more than 100 sampling points covered between 1995 and 2002.
Table 2 indicates statistical distribution of chloride in groundwater.

Table 2 - Statistical distribution of chloride in groundwater (mg/L)

Samples	Min	Q_1	Median	Average	Q_3	Máx	St dev
155	13.0	22.0	32.5	48.2	59.4	235.0	39.8

Regarding chloride in rainfall a total of 25 data concentration sampling were collected between 1997 and 2003 in the areas of Beja (7 samples), Serpa (5 samples) and Ferreira do Alentejo (13 samples).
Table 3 indicates statistical distribution of chloride in rainfall.

Table 3 - Statistical distribution of chloride in rainfall (mg/L)

Samples	Min	Q_1	Median	Average	Q_3	Máx	St dev
25	0.4	2.2	3.4	4.2	5.5	13.4	3.3

The application of equation [1] to inter-quartile interval (Q_1 to Q_3) and not including extreme values indicates average recharge of 10% of annual rainfall.

3.2 Daily Sequential Water Balance – EARTH Model

Model EARTH used daily information of groundwater levels from 3 piezometers. According the hydraulic characteristics of soils and vadose zone it was decided to run EARTH model for field capacity of 100 mm. Other input parameters were obtained trough the bibliography and recent field work.
Recharge was computed for hydrologic years of 2001/2002 and 2002/2003. The daily values of precipitation and potential evapotranspiration were determined for the Beja region. Potential evapotranspiration was considered equal to reference evapotranspiration determined by the FAO Penman-Monteith method (Allen *et al.* 1998).
The values obtained with the EARTH model are summarised in Table 4.

Table 4 – Annual recharge of "Gabbros of Beja" for the hydrologic years 2001/2002 and 2002/2003 based on 3 piezometres (EARTH model)

Hydrologic Year (FC = 100 mm)	Precip. (mm)	Recharge (mm)	Recharge (%)
2001/2002	652	326-391	50-60
2002/2003	537	269-322	50-60
Average	595	327	50-60

The analysis of the results obtained with the EARTH model, indicates recharge in the order of 50% for 2001/2003 considering 100 mm for field capacity.

3.3 Daily Sequential Water Balance – BALSEQ Model

Accordingly the hydraulic characteristics of "Gabbros of Beja" ("Beja clays"), it was decided to run BALSEQ model for *AGUT* values of 100 and 120 mm. The cereals crop in a soil type D is assigned *NC* = 85.
Recharge was computed for hydrologic years of 2001/2002 and 2002/2003. The daily values of precipitation and potential evapotranspiration were determined for the Beja region. Potential evapotranspiration was considered equal to reference evapotranspiration determined by the FAO Penman-Monteith method (Allen *et al.* 1998).
The values obtained with the daily sequential water balance are summarised in Table 5 considering AGUT of 100 mm.

Table 5 – Annual recharge of "Gabbros of Beja" for the hydrologic years 2001/2002 and 2002/2003 (BALSEQ model)

Hydrologic Year (AGUT = 100 mm)	Precip. (mm)	Recharge (mm)	Recharge (%)
2001/2002	652	36	6
2002/2003	537	82	15
Average	595	59	11

The analysis of the results obtained with the BALSEQ model, indicates that despite the 2001/2002 hydrologic year presents a precipitation 20 % larger than the 2002/2003 hydrologic year, corresponding recharge is much lower. This is due to the seasonal distribution of precipitation, and specially, to the torrential episodes of precipitation in 2001/2002 hydrologic year.
For water resources management purposes, in an annual or hydrologic year basis, among the methods used herein, the BALSEQ model is expected to be the best approach to quantify water availability.

By assuming maximum amount of water available for evapotranspiration (*AGUT*) in the order of 100 mm, average annual recharge may vary between 6 % and 15 % (of annual precipitation), with average values for the considered hydrologic years around 11%.

3.4 Annual Water Balance (pumping rates)

Beja Municipality data indicate that pumping rates for public consumption was around 4,000 a 5,000 m^3/day from 16 wells located in Pisões catchment, meaning an average of 1,650,000 m^3/year.
Pisões catchment has 20 km^2 area and develops in gabbro-dioritic rocks (Gabbro aquifer) meaning that, in each km^2, around 80,000 m^3 of water can be abstracted per year, even during drought periods. This represents an average availability for exploitation of 83 mm/year.
In a long-term basis, assuming that groundwater discharge from the system is minimum, this average exploitation of 83 mm/year may be assumed to reflect average groundwater recharge. This value represents 14% of average annual precipitation (584 mm/year) (Paralta 2001).

5. CONCLUSIONS

Results of direct and indirect methods show that annual average recharge in the "Gabbros of Beja" should be between 10% and 20% of average annual rainfall or even more considering daily sequential model EARTH.
According to the annual water balance based on historical data and to the chloride mass balance groundwater recharge is between 10% and 14%.
Using the daily sequential water balance modelling of hydrological parameters based on BALSEQ model, results for the hydrologic years of 2001/2002 and 2002/2003, considering 100 mm for AGUT, indicate recharge around 11%.
The same basic input parameters were used in EARTH model, such as daily rainfall, PET and field capacity, among other specific model inputs, giving a recharge around 50% after piezometric curve calibration.
Recharge modelling shows that it is necessary to make a critical review of EARTH input parameters and adjust their physical meaning to the specific case study (gabbro unconfined shallow aquifer). Increasing field capacity corresponds to lowering recharge; so, further work is needed regarding hydraulic characterization of soils and vadose zone and longer daily climatic series.
According to the results, average groundwater recharge in "Gabbros of Beja" Aquifer System should be at least between 50 and 100 mm/year (10 to 20% of the average annual rainfall) giving an amount of groundwater annual renewable resources between 17.5×10^6 m^3 and 35.0×10^6 m^3 for the entire aquifer (350 km^2).

ACKNOWLEGMENTS

The author's wishes to express their gratitude to FCT – Science and Technology Foundation (Portugal) for the project financial support and PhD scholarship.
We would also like to thank ITC staff, namely Professor Macieck Lubczynski and Dr. Rafael Cortez, for their support during field work and modelling effort.

REFERENCES

Allen RG, Pereira LS, Raes D & Smith M (1998) – Crop evapotranspiration – Guidelines for computing crop water requirements. FAO, Irrigation and Drainage Paper, nr. 56.

Chachadi AG, Moinante MJ & Oliveira MM (2002) – Measuring, Monitoring and Managing Sustainability: The Coastal Dimension – Coastin. Gis and Mathematical Modelling for the Assessment of Groundwater Vulnerability to Pollution: Application to an Indian Case-Study Area in Kakinada. Lisboa, Laboratório Nacional de Engenharia Civil, Relatório 279/02 – GIAS, October/2002, 43 pp.

Chachadi AG, Raikar PS, Lobo Ferreira JP & Oliveira MM (2001) – GIS and Mathematical Modelling for the Assessment of Groundwater Vulnerability to Pollution: Application to an Indian Case Study Area in Goa. Lisboa, Laboratório Nacional de Engenharia Civil, Relatório 115/01-GIAS, April 2001,69 pp.

Duque JM (2005) – *Hidrogeologia do Sistema Aquífero dos Gabros de Beja*. Tese de Doutoramento. Faculdade de Ciências da Univ. de Lisboa. Lisboa, 420 pp.

Duque JM (1997) – *Caracterização hidrogeológica e modelação matemática do aquífero dos Gabros de Beja*. Tese de Mestrado, Faculdade de Ciências da Universidade de Lisboa. Lisboa, 210 pp.

Gouweleeuw BT (2000) – *Satellite passive microwave surface moisture monitoring*. Thesis, Vrije Universiteit, Amsterdam. The Netherlands.

Jackson JT (2002) – Remote sensing of soil moisture: implications for groundwater recharge. Hydrogeology Journal (2002), 10:40-51. DOI 10.1007/s10040-001-0168-2.

Lobo Ferreira JP (1981) – Mathematical model for the evaluation of the recharge of aquifers in semiarid regions with scarce (lack) hydrogeological data. Proceedings of Euromech 143/2-4 Setp. 1981, Rotterdam, A.A. Balkema (Ed. A. Verruijt e F.B.J. Barends).

Lobo Ferreira JP, Baptista JM, Rodrigues JD & Cunha LV (1981) – Estudo global dos recursos hídricos da ilha do Porto Santo. Lisboa, Laboratório Nacional de Engenharia Civil.

Oliveira MM, Moinante MJ & Lobo Ferreira JP (1997) – Cartografia Automática da Vulnerabilidade de Aquíferos com Base na Aplicação do Método DRASTIC. Relatório Final. Lisboa, LNEC, Relatório 60/97-GIAS, 535 pp.

Oliveira MM, Moinante MJ & Lobo Ferreira JP (1994) – Estudo da Caracterização dos Aquíferos e dos Consumos de Água na Península de Setúbal. Contribuição do LNEC para o Relatório da HP a Entregar à EPAL em Fevereiro de 1994. Lisboa, Laboratório Nacional de Engenharia Civil. Relatório 37/94 – GIAS.

Paralta E, Fernandes R, Carreira P & Ribeiro L (2005a) – Assessing the impacts of agriculture on groundwater quality using nitrogen isotopes – preliminary results on the "Gabbros of Beja" Aquifer System (South Portugal)**.** 2nd Workshop of the Iberian

Regional Working Group on Hardrock Hydrogeology, 18-21 May, Évora, Portugal, 14 pp.

Paralta E, Francés A & Ribeiro L (2005b) – Avaliação da Vulnerabilidade do Sistema Aquífero dos Gabros de Beja e Análise Crítica das Redes de Monitorização no Contexto da Directiva Quadro da Água. Actas/CD do VII Simpósio de Hidráulica e Recursos Hídricos dos Países de Língua Oficial Portuguesa (SILUSBA), Évora, 30 de Maio a 2 de Junho de 2005, 16 pp.

Paralta E, Oliveira M, Lubczynski M & Ribeiro L (2003) – Avaliação da recarga do Sistema Aquífero dos Gabros de Beja segundo critérios múltiplos – disponibilidades hídricas e implicações agro-ambientais. Publicações do VI Simpósio de Hidráulica e Recursos Hídricos dos Países de Língua Oficial Portuguesa (SILUSBA), Vol. 2. Cabo-Verde, Praia, 10 a 13 de Novembro de 2003, 501-516 pp.

Paralta E & Ribeiro L (2003) – Monitorização e Modelação Estocástica da Contaminação por Nitratos do Aquífero Gabro-diorítico na Região de Beja – Resultados, Conclusões e Recomendações. Seminário sobre Águas Subterrâneas. LNEC, 27-28 de Fevereiro de 2003, Lisboa, 30 pp.

Paralta (2001) – *Hidrogeologia e Modelação Estocástica da Contaminação por Nitratos do Aquífero Gabro-diorítico da Região de Beja*. Tese de Mestrado em Georrecursos. IST/Centro de Geo-Sistemas, Lisboa, 157 pp.

Paralta E & Ribeiro L (2001) – Stochastic modelling and probability risk maps of nitrate pollution in the vicinities of Beja (Alentejo, south Portugal). 3rd International Conference on Future Groundwater Resources at Risk, Unesco, Lisbon, 11 pp.

Paralta E & Francés A (2000) – Caracterização hidrogeológica e avaliação da vulnerabilidade à poluição do complexo gabro-diorítico de Serpa-Brinches (sector oriental do sistema aquífero dos Gabros de Beja). GeoNovas, nº14, Porto, pp. 27-35.

Paralta E & Ribeiro L (2000) – Análise variográfica e cartografia de risco da contaminação por nitratos na região de Beja. Recursos Hídricos, APRH, vol. 21, nº3, Lisboa, pp. 47 – 58.

Scanlon BR, Healy RW & Cook PG (2002) – Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology Journal (2002), 10:18-39. DOI 10.1007/s10040-001-0176-2.

Serra E (2002) – *Vulnerabilidade e risco de poluição agrícola no sistema aquífero dos Gabros de Beja (sector da margem esquerda do rio Guadiana)*. Trabalho Final de Curso de Licenciatura em Engenharia do Ambiente. Instituto Superior Técnico, Lisboa 2002, 87 pp.

Van der Lee & Gehrels J C (1990) – Modelling Aquifer Recharge. Introduction to the Lumped Parameter Model EARTH. Hydrological Report, Free University of Amsterdam. The Netherlands, 1990, 30 pp.

Vermeulen H, Lobo Ferreira JP, Oliveira MM (1993) –A method for estimating aquifer recharge in DRASTIC vulnerability mapping. Comunicação apresentada ao seminário

"Águas Subterrâneas e Ambiente", realizado pela Associação Portuguesa dos Recursos Hídricos (APRH) em Lisboa, em Maio de 1993.