Water in Celtic Countries: Quantity, Quality and Climate Variability (Proceedings of the Fourth InterCeltic Colloquium on Hydrology and Management of Water Resources, Guimarães, Portugal, July 2005).
IAHS Publ. 310, 2007.

On wellhead protection assessment methods: a case study in Montemor-o-Novo, Portugal

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Abstract Groundwater is vulnerable to several kinds of pollution usually related to the development of anthropogenic activities. Nowadays, wellhead protection areas and their associated restrictions are the most widely used instruments for protecting aquifers. After the description of the wellhead protection area and the presentation of Portuguese regulations that govern wellhead protection areas, a review of the methods applied to define wellhead protection areas in the case study is presented. The study area is briefly described, including the wells used for public water supply, and analytical methods for wellhead protection zone definition are applied, including the method suggested by the Portuguese legislation and the ASMWIN numerical model. Finally, some conclusions are made, based on the results achieved.

Key words analytical method; aquifer protection; groundwater; numerical modelling; pollution; stochastic modelling

INTRODUCTION

When an aquifer becomes seriously polluted, the re-establishment of its natural quality becomes very difficult, even if the pollutant source is already inactive. Usually, the pollution of an aquifer is detected a long time after the start of the first pollution event and, by that time, the polluted volume of the aquifer may be considerable. One preventive instrument to assure the protection of groundwater resources used for public supply is to set up restrictions on land use around wells. The definition of wellhead protection areas (WHPA) around wells is intended to avoid the need for large projects associated with groundwater rehabilitation and also to protect and assure their quality for future generations.

WELLHEAD PROTECTION AREA (WHPA)

The WHPA is the surface and subsurface area around a well the limits of which are defined to assure that potential bacteriological contaminants, after reaching groundwater inside or outside protection zones, become harmless before reaching the well. Groundwater resources polluting activities are prohibited or restricted inside the WHPA.

The Portuguese law (*Decreto-Lei* 382/99, of 22 September 1999) refers to the following protection zones:

– Zone of immediate protection: the area around the well in which, by default, all activities are prohibited except those for conservation, maintenance or better exploration of the aquifer.

– Zone of intermediate protection: area around the zone of immediate protection with variable extension, in which the objective is to reduce or eliminate pollution of the groundwater resources. Installations or activities that potentially may pollute groundwater resources are prohibited or restricted; this includes infiltrating pollutants, or favouring infiltration in the zone close to the well (e.g. agricultural use or cattle rearing, main roads and railways, industrial units, sanitary landfills, garages and gas stations).
– Extended zone of protection: area around the zone of intermediate protection in which activities are prohibited or restricted regarding installations capable of polluting groundwater resources with persistent pollutants, taking into account the nature of the terrain, the nature and quantity of pollutants as well as the type of emission of these pollutants (e.g. application of persistent pesticides, cemeteries, transport of hydrocarbons, radioactive materials or other hazardous substances, deposits of radioactive materials, chemical industries and refineries).
– In the case of karstic or fractured aquifers where preferential flow paths exist, special protection zones can be set up. These zones limit areas located outside the WHPA that are characterized by hydraulic connection with the well due to the existence of fractures or fissures. The restrictions are similar to those applied inside the zone of immediate protection.

In coastal regions, saltwater intrusion protection zones can be defined, inside which extraction rates that might lead to an eventual degradation of groundwater quality, by favouring saltwater intrusion, are limited. The construction or exploitation of new wells can be limited and the exploitation regime can also be conditioned.

Finally, quantity protection zones can also be defined. Inside these zones the volumes to be pumped out are limited to assure groundwater quantity.

WHPA DELINEATION METHODS APPLIED TO THE MONTEMOR-O-NOVO REGION

The WHPA benefits do increase with the complexity of the method used for its definition. On the other hand, the associated costs, expertise, and the needs for more refined information also increase. Nevertheless, costs associated with groundwater protection are largely compensated when compared to the costs and difficulties associated with rehabilitation of a polluted aquifer. The method used reflects the criteria selected in a previous step; one can use more than one method in the delineation of a WHPA,

In the study on which this article is based (Moinante, 2003), the following analytical methods were used in the definition of WHPA around wells located in the Montemor-o-Novo region: Calculated Fixed Radius method, Wyssling method and Krijgsman & Lobo-Ferreira method. The mathematical model ASMWIN was also applied.

Calculated Fixed Radius (CFR) – method suggested by Portuguese law

According to the Portuguese law, all groundwater extraction wells designed for public water supply shall have a zone of immediate protection. Wells extracting water for

Table 1 Minimum value of protection zone radii when using the CFR method.

Type of aquifer system	Immediate zone	Intermediate zone	Extended zone
Type 1	r = 20 m	r = largest value between 40 m and r_1 (t = 50 days)	r = largest value between 350 m and r_1 (t =3500 days)
Type 2	r = 40 m	r = largest value between 60 m and r_2 (t = 50 days)	r = largest value between 500 m and r_2 (t =3500 days)
Type 3	r = 30 m	r = largest value between 50 m and r_3 (t = 50 days)	r = largest value between 400 m and r_3 (t =3500 days)
Type 4	r = 60 m	r = largest value between 280 m and r_4 (t = 50 days)	r = largest value between 2400 m and r_4 (t =3500 days)
Type 5	r = 60 m	r = largest value between 140 m and r_5 (t = 50 days)	r = largest value between 1200 m and r_5 (t =3500 days)
Type 6	r = 40 m	r = largest value between 60 m and r_6 (t = 50 days)	r = largest value between 500 m and r_6 (t =3500 days)

public supply with a discharge greater than 100 m^3 day^{-1} or serving more than 500 inhabitants shall have three protection zones (immediate, intermediate and extended).

The CFR method as it is presented in the Portuguese law, considers six types of aquifer systems: confined porous (Type 1); unconfined porous (Type 2); semi-confined porous (Type 3); limestone (Type 4); aquifer consisting of igneous or metamorphic fissured formations (Type 5); aquifer consisting of igneous or metamorphic poorly fissured formations (Type 6). The minimum values of the required protection zones for these six aquifer types are presented in Table 1.

The value of r_i is a variable distance that can be calculated using the following equation:

$$r_i = [(Q\ t) / (3.14\ n\ b)]^{1/2} \qquad (1)$$

where r_i is the radius of protection perimeter (m), Q is the extraction rate (m^3 day^{-1}), t is the time necessary for a pollutant to enter the well (days), n is the effective porosity and b is the saturated thickness in the well (m). The limitation of this method is that it does not take into account the regional groundwater flow causing a hydraulic gradient. It thus can only be applied in situations where a (near-) horizontal initial (before pumping) water table is present. The cone of depression resulting from pumping will then be a circle around the well and with equation (1) the radius of the circle can be calculated, corresponding to a travel time distance of 50 days.

The consequence of this is that by using this method in situations with a non negligible hydraulic gradient, the calculated perimeter of a protection zone may be inadequate on the upgradient side, while on the downgradient side the extension of the zone is over dimensioned. This may result in an overprotected downgradient area with unnecessary economic consequences, while the other side is under protected resulting in an increased danger of pollutants entering the well.

Wyssling method

This is an easy to apply method that can be used for porous homogeneous aquifers. The method considers wells in extraction and the existence of a sloping hydraulic gradient, resulting in an asymmetrical cone of depression. This method uses the following equations to calculate the dimensions of two protection distances (S_0 and S_u):

$$Q = K\,B\,b\,i \Leftrightarrow B = Q / (K\,b\,i) \quad (2)$$

$$X_0 = Q / (2\,\pi\,K\,b\,i) \quad (3)$$

$$B' = B / 2 = Q / (2\,K\,b\,I) \quad (4)$$

$$v_e = (K\,i) / n \quad (5)$$

$$l = v_e\,t \quad (6)$$

$$S_0 = [+\,l + (l\,(l + 8\,X_0))^{1/2}] / 2 \quad (7)$$

$$S_u = [-\,l + (l\,(l + 8\,X_0))^{1/2}] / 2 \quad (8)$$

where K is the hydraulic conductivity (m day^{-1}), i is the hydraulic gradient, X_0 is the distance between the well and the null flow point (downgradient flow boundary), B' is the maximum width of the upgradient zone of contribution, v_e is the effective velocity (m day^{-1}), S_0 is the upgradient distance equivalent to travel time t (m) and S_u is the downgradient distance equivalent to travel time t (m).

Krijgsman & Lobo-Ferreira method

This method was developed for the assessment of the intermediate protection zone (t = 50 days) and is an alternative to hydrogeological studies referred to in the Portuguese legislation. Using this method one can quickly and without much effort give ranges of perimeters for the required protection zones. This methodology is for use in unconfined aquifers, since these are the most directly vulnerable to pollution.

According to Krijgsman & Lobo-Ferreira (2001), the 50 days protection zone has an ellipse-shaped form which will be more like a circle when the hydraulic gradient is smaller. These authors suggest the use of three equations to calculate the dimensions of the three protection distances of the intermediate zone ($r_{\max}$, $r_{\min}$ and r_p) (Fig. 1).

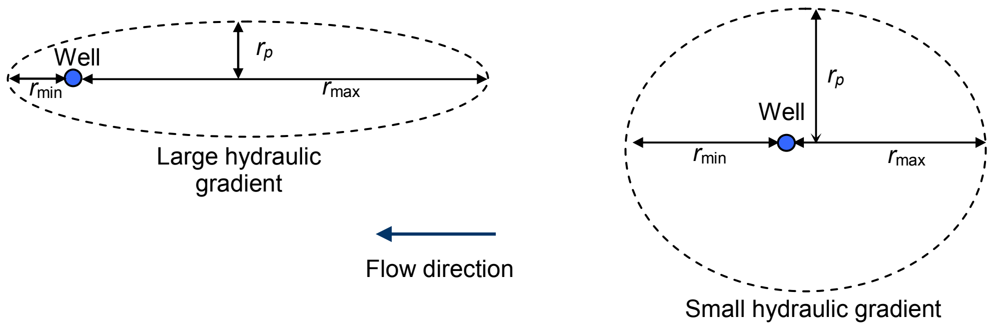

Fig. 1 Intermediate protection zone in extreme situations of hydraulic gradient (adapted from Krijgsman & Lobo-Ferreira, 2001).

Upgradient protection distance

$$r_{\max} = (0.00002x^5 - 0.00009x^4 + 0.015x^3 + 0.37x^2 + x) / F \quad (9)$$

Downgradient protection distance

$$r_{\min} = (-0.042x^3 + 0.37x^2 - 1.04x) / F \quad (10)$$

Protection distance perpendicular to flow direction

$$r_p = 4\,(Q / n\,b)^{1/2} \quad (11)$$

with $x = 2\,K\,i\,[(\pi\,b\,t) / (Q\,n)]^{1/2}$ and $F = (2\,\pi\,K\,b\,i) / Q$. (12) and (13)

Limitations on the use of these equations:
(a) $r_{\max}$: do not use combinations of parameters resulting in a value of $x > 18$;
(b) $r_{\min}$: if $x < -3.5$ apply a minimum protection distance of 25 m; do not apply equation (10) with values of effective porosity < 0.1 (10%).

In fact, the 50 days protection zone is never a perfect ellipse, especially in cases with large hydraulic gradients. The more the area resembles a circle, the better the estimation will be. Krijgsman & Lobo-Ferreira (2001) suggest a modification of the ellipse on its upgradient side, by drawing a circle on the edge of the ellipse with a radius equal to r_p (Fig. 2).

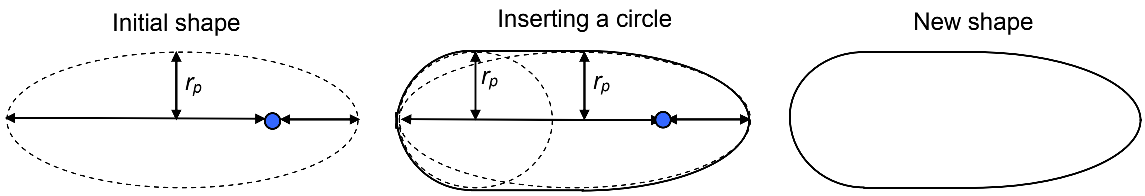

Fig. 2 Modification of the upgradient limit of the ellipse (adapted from Krijgsman & Lobo Ferreira, 2001).

Brief introduction to mathematical groundwater flow model ASMWIN

ASMWIN is a two dimensional groundwater flow and transport model. It includes a finite-difference flow model, a tool for the automatic calibration of a flow model, a particle tracking model, a random walk transport model, a finite-difference transport model and several other useful modelling tools. It can handle grids with up to 150 × 150 cells and 1000 time periods (pumping intervals). The particle tracking module ASMPATH allows the computation of flow paths and travel times. Both forward and backward particle tracking schemes are feasible for steady-state and transient flow fields. ASMPATH calculates and shows pathlines, flowlines and travel time marks simultaneously (Chiang *et al*., 1998).

CHARACTERIZATION OF THE CASE STUDY AREA

The wells selected by Moinante (2003) for the application of the WHPA delineation methods are located in the Montemor-o-Novo aquifer, which belongs to the Évora-Montemor-Cuba aquifer system, in the southern Portuguese region of Alentejo. The aquifer occupies an area of 373 km^2, has a SE–NW orientation, and is located in Montemor-o-Novo and Évora municipalities and in the Tejo and Sado river basins.

The Montemor-o-Novo aquifer presents an igneous and metamorphic constitution, being a heterogeneous medium where groundwater flows: (a) in porous media, in the upper altered part, (b) in double porosity media in the intermediate zone, and (c) in fractured media, in the bottom, near the bedrock (Streltsova, 1976, in Fialho *et al*., 1998). The weathered depth of the aquifer varies between 20 and 60 m and the majority of the wells located in this region explore the altered formations. Due to the degree of alteration, this phreatic aquifer has detritic characteristics (clayey sand) with an effective porosity (n) of 10%. According to Portuguese law, this is the minimum value to use in case of porous formations.

Wells used for public supply

In Moinante (2003) seven wells used for public water supply, located in the Amoreira da Torre area (5 km NNE of Montemor-o-Novo), were selected for a case study (Fig. 3).

The Montemor-o-Novo municipality is supplied exclusively by groundwater, assured by several water supply systems. Montemor-o-Novo is also the name of one of those systems and supplies nearly 7500 inhabitants. The selected wells are included in the system and constitute the Amoreira da Torre sub-system. The wells' characteristics are presented in Table 2, based on the drillers reports. Only two values of transmissivity (T) are given (wells TD6B and JFF3) and used for the calculation of hydraulic conductivity (K). For the rest of the wells a value of 6 m day^{-1} was assumed (Table 3). The hydraulic gradient was calculated using a Digital Elevation Model (DEM). The phreatic level is, in most cases, very close to the land surface so the phreatic surface was assumed to be parallel to the topography. Table 4 presents the hydraulic gradient for the seven wells and also the extraction rates.

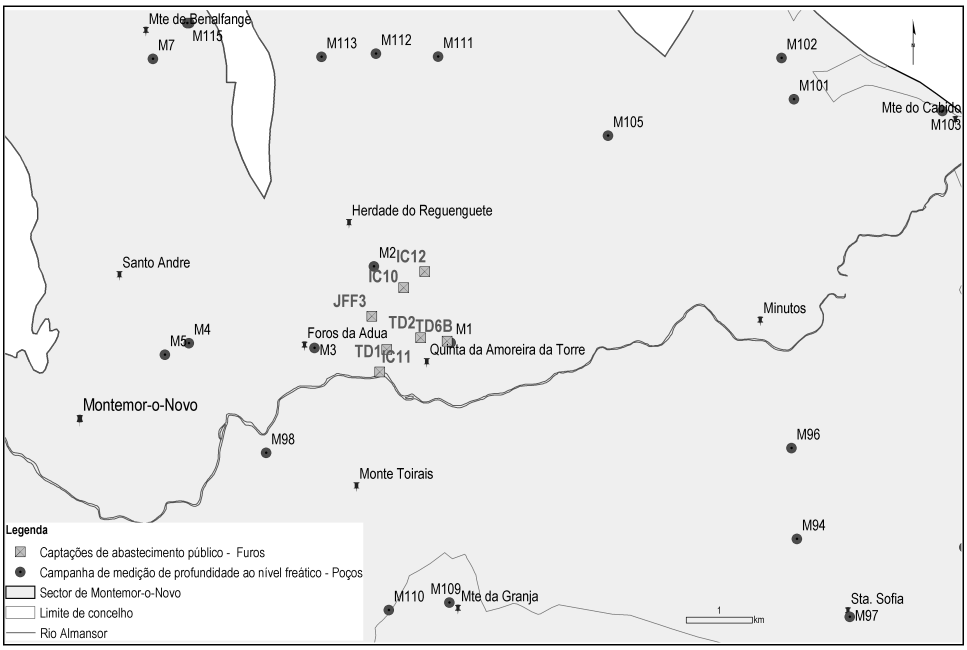

Fig. 3 Wells used for public water supply and selected for the case study.

Table 2 Case study wells characteristics (Amoreira da Torre public supply sub-system).

Well	M (m)	P (m)	Elevation (m)	Depth (m)	Phreatic level depth (m)	Depth of aquifer bottom (m)	Saturated thickness (m)	Date
TD1	197396	187822	234	31	0.8	22	21.2	12/10/1976
TD2	197910	188000	236	31	0.9	17	16.1	12/10/1976
TD6B	198310	187950	236	31	3.6	31	27.4	17/11/1977
JFF3	197169	188326	238	45	1.56	21	19.44	05/02/1996
IC10	197652	188754	244	49	4.3	–	25*	14/02/2000
IC11	197292	187483	219	85	3	–	25*	14/02/2000
IC12	197971	188998	250	65	5	–	25*	14/02/2000

* Assumed value for *b*; no log was included in the well construction report.

Table 3 Transmissivity and hydraulic conductivity in wells TD6B and JFF3.

Well	Transmissivity (T) (m^2 day^{-1})	Hydraulic conductivity ($K = T/b$) (m day^{-1})
TD6B	173	6.3
JFF3	115	5.9
Other wells	–	6

Table 4 Hydraulic gradient and extraction rates in case study wells.

Well	Hydraulic gradient	Extraction rate (m^3 day^{-1})
TD1	0.022	200.8
TD2	0.014	278.8
TD6B	0.013	6.3
JFF3	0.01	25.3
IC10	0.02	252
IC11	0.023	252
IC12	0.034	252

DEFINITION OF WHPA USING ANALYTICAL METHODS AND A NUMERICAL METHOD

The selected analytical methods for the definition of WHPA were those described earlier and the travel time values used were: (a) 24 hours, for the immediate zone (according to ITGE, 1991), despite the fact that the Portuguese legislation refers to a fixed value for this zone radius, (b) 50 days, for the intermediate zone (according to Portuguese legislation), and (c) 3500 days, for the extended zone (also according to Portuguese legislation). The values obtained using the different methods are presented in Tables 5 to 7.

After comparing all the results obtained with the analytical methods, Moinante (2003) concluded that, by assessing the dimensions of three protection zones, the Krijgsman & Lobo-Ferreira method makes the delineation of protection zones an easier and more precise task.

ASMWIN was also used and an area of approximately 39 km^2 was modelled. Only one layer with variable thickness representing the phreatic aquifer was considered. The input data was the following: initial piezometry taken from the DEM; hydraulic conductivity (K) = 6 m day^{-1}; effective porosity (n) = 0.1; recharge = 170 mm $year^{-1}$ =

Table 5 Values obtained for the dimensions of the immediate zone using analytical methods.

Well	Calculated fixed radius	Wyssling		Krijgsman & Lobo Ferreira	
		upgradient	downgradient	upgradient	downgradient
TD1	5.5	6.2	4.9	6.5	4.8
TD2	7.4	7.9	7	8	7.1
TD6B	0.9	1.4	0.5	1.5	0.4
JFF3	2	2.4	1.8	2.5	1.7
IC10	5.7	6.3	5.1	6.6	5
IC11	5.7	6.4	5	6.7	4.9
IC12	5.7	6.8	4.7	7.2	4.5

Table 6 Values obtained for the dimension of the intermediate zone using analytical methods.

Well	Calculated fixed radius	Wyssling		Krijgsman & Lobo Ferreira		
		upgradient	downgradient	upgradient	downgradient	perpendicular
TD1	38.8	84	18	93.1	25	38.9
TD2	52.5	77.6	35.6	85.4	29.2	52.6
TD6B	6.1	41.7	0.9	43.4	25	25
JFF3	14.4	35.4	5.9	39	25	25
IC10	40.1	80.1	20.1	88.9	25	40.2
IC11	40.1	86.5	18.6	95.9	25	40.2
IC12	40.1	115.9	13.9	126.8	25	40.2

Table 7 Values obtained for the dimension of the extended zone using analytical methods.

Well	Calculated fixed radius	Wyssling	
		upgradient	downgradient
TD1	324.9	4627.7	22.7
TD2	439.3	3004.2	64.2
TD6B	50.6	2857.4	0.9
JFF3	120.4	2072	7
IC10	335.2	4226.6	26.6
IC11	335.2	4777.1	23.5
IC12	335.2	7155.7	15.7

0.0005 m day^{-1} (Oliveira, 2002). After calibration, the module ASMPATH was used with the option of backward particle tracking. In this way it was possible to obtain the pathways followed by the particles during the pre-defined travel times. As an example, the extended zones of protection, obtained using $t = 3500$ days, are shown in Fig. 4.

Using the flow model created earlier and also *Field Generator*, a modelling tool that uses the Monte Carlo method to generate lognormal distributions of hydraulic conductivity or transmissivity, different heterogeneous distributions of K were obtained and re-used in ASMWIN and ASMPATH. Figure 5 presents some examples of the new pathlines, drawn using new K heterogeneous distributions and $t = 3500$ days (extended zone of protection). Using some stochastic simulations, it was possible to gain an idea of the uncertainty related to the distribution of hydraulic conductivity and the influence of this parameter in pathlines and travel times of pollutant particles.

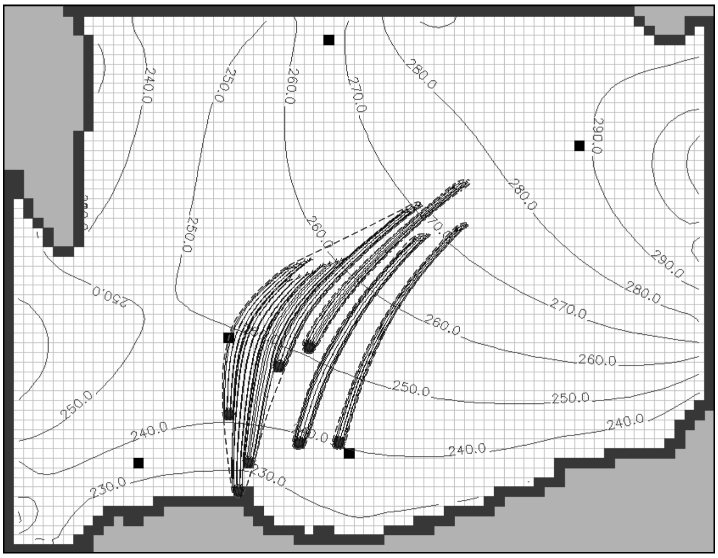

Fig. 4 Pathlines for $t = 3500$ days (extended protection zones).

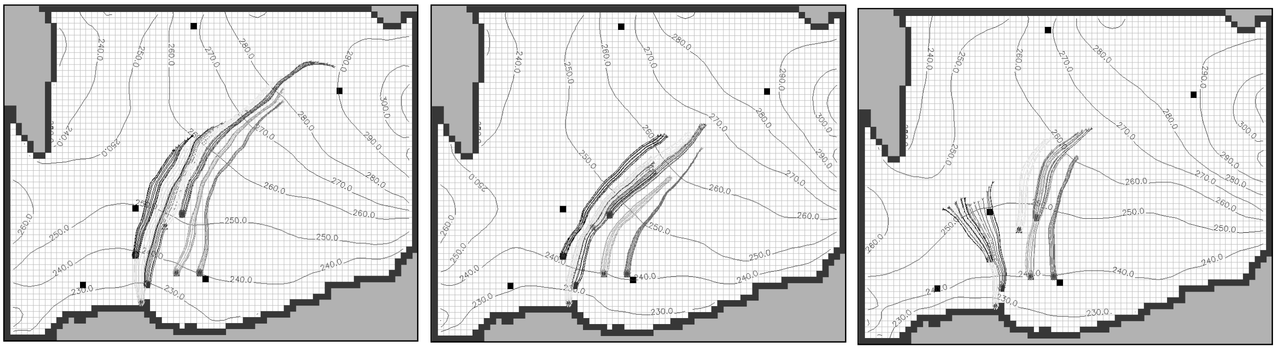

Fig. 5 Extended protection zones obtained with new K heterogeneous distributions and $t = 3500$ days.

CONCLUSIONS

Analytical methods are user friendly and easy to apply, and some of them, like the Krijgsman & Lobo-Ferreira method, can give sound solutions and also more precision in the delineation of WHPA.

Numerical models can also give robust solutions in the case of complex hydrogeological systems, but their use implies the availability of large amounts of complex information and also more expertise, which makes their application more expensive.

Furthermore, numerical modelling results can be improved by the use of stochastic approaches, once they allow generation of heterogeneous distributions of K. The new WHPA can assume different shapes depending on the spatial distribution of K, highlighting the uncertainty related with the distribution of this parameter inside the aquifer and its importance in the definition of WHPA.

REFERENCES

Chiang, W.-H., Kinzelbach, W. & Rausch, R. (2003) *ASMWin – Aquifer Simulation Model for Windows* 6.0. Zurich: Institute of Hydromechanics and Water Resources Management (IHW) – Swiss Federal Institute of Technology: Zurich, Switzerland.

Fialho, A., Chambel, A. & Almeida, C. (1998) Caracterização Hidráulica de Aquíferos Fracturados por Modelos de Porosidade Dupla no Concelho de Évora. In: *4º Congresso da Água: A Água como Recurso Estruturante do Desenvolvimento* (23–27 March 1998). Associação Portuguesa dos Recursos Hídricos, Lisbon, Portugal.

ITGE (1991) Guía Metodológica para la Elaboración de Perímetros de Protección de Captaciones de Aguas Subterráneas. Instituto Tecnológico GeoMinero de España, Madrid, Spain.

Krijgsman, B. & Lobo-Ferreira, J. P. C. (2001) *A Methodology for Delineating Wellhead Protection Areas*. Laboratório Nacional de Engenharia Civil, INCH 7, Lisbon, Portugal. ISBN 972-49-1882-3.

Moinante, M. J. (2003) Delimitação de Perímetros de Protecção de Captações de Águas Subterrâneas. Estudo Comparativo Utilizando Métodos Analíticos e Numéricos. LNEC Master Theses – TM 11. Laboratório Nacional de Engenharia Civil, Lisbon, Portugal.

Oliveira, M. M. (2002) Cartografia da Vulnerabilidade à Poluição das Águas Subterrâneas do Concelho de Montemor-o-Novo Utilizando o Método DRASTIC. Laboratório Nacional de Engenharia Civil, Report 46/02 – GIAS, Lisbon, Portugal.