Models for wellhead protection in regional unconfined aquifers and stratified aquifers

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RESUMEN

En este trabajo son presentados los conceptos matemáticos usados para el desarrollo de la protección de cabezales de pozos y la metodología de zonificación. Ellos están basados en soluciones analíticas, en el flujo del agua subterránea y en la modelación en diferencias finitas del rastreo de partículas. Los límites de la protección de cabezales de pozos están en función no sólo de la geología local, de los parámetros del acuífero y de las características regionales del acuífero, también de los caudales de extracción (o de la productividad del acuífero). Verticalmente el análisis fue realizado usando un modelo de flujo simétrico a un eje asumiendo que el flujo de agua subterránea hacia el pozo es radial. Las herramientas matemáticas fueron desarrolladas para ser robustas y de uso amigable, facilitando la aplicación de la nueva legislación portuguesa relacionada con la protección del agua subterránea. La aplicación de la metodología es ejemplificada en dos estudios de caso, uno desarrollado para el acuífero costero de Bardez, en el estado de Goa, India y el otro en Ramahal, Portugal.

PALABRAS CLAVE: Flujo del agua subterránea, protección de cabezales de pozos, modelación numérica, modelación en diferencias finitas, rastreo de partículas, contaminación.

ABSTRACT

Mathematical concepts are used for the development of wellhead protection and zoning methodologies, based on analytical solutions and on groundwater flow and particle tracking finite differences. Wellhead protection limits are a function of the local geology, of the aquifer parameters and the regional hydraulic characteristics of the aquifer, and of the extraction rates or of the productivity of the aquifer. In the vertical dimension the analysis was performed using an axisymmetric flow model, assuming that groundwater flow into the well is radial. The radial axisymmetric mathematical tools were robust and user friendly, facilitating the application of the new Portuguese legislation regarding groundwater protection. The methodology is exemplified in two case studies, one for the coastal aquifer of the Bardez, Goa State, India and the other in Ramalhal, Portugal.

KEY WORDS: Groundwater flow, wellhead protection zones, numerical modeling, finite difference modeling, particle tracking, contamination.

1. INTRODUCTION

Groundwater resources constitute an important source of water and are important to be preserved. The quality of groundwater resources can be affected by social-economic activities, especially in the case of using and occupying the soil, such as with urban areas, infrastructures, agriculture, etc.

The contamination of the groundwater resources is, in general, persistent, so that the recuperation of the water quality is a slow and difficult process (Leitão, 1997). The protection of the groundwater resources is therefore a strategic objective of major importance. It is important to develop an equilibrated and durable use of these resources.

One preventive instrument to assure the protection of the groundwater resources used for abstraction is setting up protection zones around wells extracting groundwater for public supply. The limits of these areas are a function of the geology, hydraulic characteristics of the concerned aquifer and amount of extracted water. In these defined areas around wells, restrictions should be set up concerning public use and changes of soil uses, in order to protect the quality of the groundwater resources beneath it.

Protection zones around wells are generally defined as travel time zones, either to allow for the attenuation of concentrations of contaminants in the aquifer or to provide a monitoring zone. If a contamination is detected in a monitoring zone, it could be dealt with it before it enters the well. The objective of this project (Krijgsman and Lobo-Ferreira, 2001, and Feseker and Lobo-Ferreira, 2001) was to develop a methodology to delineate the dimensions of such protection zones, in this special case the one corresponding with a

travel time of 50 days. This in order to follow the Portu-guese Decreto-Lei nº 382/99 of September 22, 1999, which states that groundwater extraction wells should be protected against pollutants, giving for this three zones, one of which corresponds with a travel time of 50 days.

Based on experimental studies developed e.g. in German labs and according with several authors, the limit of 50 days is chosen since this is generally accepted as a limit within virus and pathogenic bacteria are naturally eliminated in groundwater, in particular E. Coli. 99.9% elimination in groundwater of E. Coli is reached after a time ranging from 10 to 100 days, as a function of the soil type, incubation temperature and soil moisture. The limit of 50 days was selected for the development of this paper methodology because, in general, it is accepted that this is the travel time that allows the elimination of virus and pathogenic bacteria in groundwater, in particular E. Coli.

For reaching this goal, hydrogeological studies have to be carried out, in order to determine the perimeters of protection zones. It is however often not possible to conduct detailed studies of individual well fields, since this involves normally considerable time and costs. Instead, it would be easier, faster and cheaper if a more general methodology was available, making possible quickly and without much effort give ranges of the perimeters of the required protection zones.

A semi-confined aquifer is by definition separated from superficial strata by a semi impermeable layer, which implies that considerable time may pass before a pollutant can enter the aquifer after entering the soil.

A confined aquifer is by definition secluded from superficial strata by an impermeable layer, such as clay, by which it is fully protected from pollutants entering the soil above it.

The output of the use of this methodology should be a map, obtained by a Geographic Information Systems (GIS), on which the required dimension of a protection zone could see in colors, without having to study the hydrogeological setting of an area into details.

In order to reach this goal, a general relationship between hydrological parameters and the dimensions of the required 50 day zone was set up, which was validated using a numerical computer program to simulate groundwater flow, Visual Modflow v. 2.7.2.

Once this relationship was validated, it was applied on a case study area in Goa, India.

2. METHODOLOGY FOR DEFINING PERIMETERS OF PROTECTION ZONES

2.1 Analytical solution

In the handbook 'Ground Water and Wellhead Protection'(EPA,1994) the following equation can be found:

$$tx = \frac{n}{Ki}\left[rx - \left(\frac{Q}{2\pi Kbi}\right)\ln\left\{1 + \left(\frac{2\pi Kbi}{Q}\right)\cdot rx\right\}\right]. \qquad (1)$$

In this equation:

t_x = time of travel (days); n = effective porosity;
K = hydraulic conductivity (m/d);
r_x = distance over which groundwater travels in tx before entering a pumping well (m), being negative (-) if downgradient and positive (+) if upgradient;
Q = discharge of pumping well (m³/d);
b = aquifer thickness (m);
i = hydraulic gradient before pumping.

Equation (1) can be used to calculate the travel time from a point x to a well, in case of a sloping hydraulic gradient, for both up- and down gradient points.

To calculate the distance as function of t, this equation should be written for r as function of t, n, K, Q, b and i.

2.2 Krijgsman and Lobo-Ferreira (2001) equations

To solve Equation (1), Krijgsman and Lobo-Ferreira (2001) developed a new methodology that may be consulted in *http://www.dha.lnec.pt/nas/english/projects/BK_LF_ICT 2001.pdf*. Equations (2), (3) and (4) have been deducted for the evaluation of the up gradient and down gradient distances and also the distance perpendicular to the flow direction:

- For the up gradient protection distance equation:

$$r = (0.00002x^5 - 0.0009x^4 + 0.015x^3 + 0.37x^2 + x)/F \qquad (2)$$

with $x = \sqrt{\dfrac{2Ft}{A}}$

and $F = 2\pi Kbi / Q$.

- For the down gradient protection distance equation:

$$r = (0.042x^3 + 0.37x^2 + 1.04x)/F. \qquad (3)$$

- For the protection distance perpendicular to the direction of flow equation:

$$r = 4\sqrt{\frac{Q}{n \cdot b}} \cdot \qquad (4)$$

2.3 Limitations

The method can not be applied, in reliable conditions, in all cases. It depends on the availability of data and on the local characteristics of the aquifer systems.

First of all, the area under analysis must be an unconfined aquifer. For confined aquifers the confining strata significantly increase the time required for the pollutant to penetrate the aquifer. The travel time through the confining strata probably would exceed 50 days. In these cases, protection zones around the well should have a minimum value, e.g. those of the already mentioned Portuguese Decreto-Lei n° 382/99 of September 1999, shown in Table 1.

A second set of requirements is related with the need of having reliable input data regarding the following parameters:

- hydraulic conductivity (K)
- water levels, from which a gradient (i) is derived
- aquifer thickness (b)
- effective porosity (n)

A problem can be the value of b. The law defines this as the saturated thickness of the aquifer in the well. It should be noted that total screen length should not be used as aquifer thickness:

- First, obtained K-values from pumping tests are an average of the total aquifer thickness, including less permeable layers within the aquifer.
- Second, if for example only the top of the aquifer is screened, than still the total thickness of the aquifer will contribute

Table 1

Minimum values for the establishment of the minimum required radii

Aquifer system type	1st protection zone / immediate zone	2nd protection zone / near zone	3rd protection zone /far zone
Type 1	$r = 20$ m	r is the highest value of 40 m and r_1 (t =50 days)	r is the highest value of 350m and r_1 (t =3500 days)
Type 2	$r = 40$ m	r is the highest value of 60m and r_2 (t =50 days)	r is the highest value of 500m and r_2 (t =3500 days)
Type 3	$r = 30$ m	r is the highest value of 50m and r_3 (t =50 days)	r is the highest value of 400m and r_3 (t =3500 days)
Type 4	$r = 60$ m	r is the highest value of 280m and r_4 (t =50 days)	r is the highest value of 2400m and r_4 (t =3500 days)
Type 5	$r = 60$ m	r is the highest value of 140m and r_5 (t =50 days)	r is the highest value of 1200m and r_5 (t =3500 days)
Type 6	$r = 40$ m	r is the highest value of 60m and r_6 (t =50 days)	r is the highest value of 500m and r_6 (t =3500 days)

Type 1 - confined aquifer system with lithological support formed by porous formations
Type 2 - unconfined aquifer system with lithological support formed by porous formations
Type 3 - semi confined aquifer system with lithological support formed by porous formations
Type 4 - aquifer system with carbonated lithological formations
Type 5 - fissured aquifer system with metamorphic and igneous formations
Type 6 - aquifer system with igneous and metamorphic formations having a small degree of fissures and weathering

to well-inflow as a result of non-horizontal flow near the screened part of the well.

With large-diameter wells, vertical flow is especially important, since an important constituent of total inflow will be bottom-inflow.

Data of extraction rates of wells (Q) are not necessarily required of all wells, since an output map can be made assuming average extraction rates. Extraction rates are never constant per well throughout a year and can vary considerably between wells, even in close wells. Depending on the area the methodology is applied depending on the density of data. Different approaches can be made:

a) If a study is made on a single well field, the output map should be based on the period (season or 50 day period) with the maximum extraction rate over a season in the well field.

b) If a study is done on a greater area, one should have some data of extraction rates to know in what range the extractions are. In that case, several maps can be made, using in one map the average and in another the maximum value of Q.

c) If plenty of data of extraction rates are available, a map can be made of the whole area showing the distribution of extraction rate and using this map in the calculation of the distribution of the needed protection area. The limitation on this is that when using the map to define protection areas for a well to be drilled, this well should have an extraction rate corresponding with the extraction rate on the input map of Q-distribution.

3. THE DELINEATION OF WELLHEAD PROTECTION ZONES IN THE VERTICAL DIMENSION

3.1 Definition of the problem

In September 1999, Portugal ratified a new law on groundwater protection. It demands three wellhead protection areas for each public water supply well that abstracts more than 100 m³ per day or serves more than 500 habitants. If the abstraction rate is lower or if the well supplies less than 500 habitants, only the immediate protection zone is required. Various activities and installations capable of polluting groundwater resources are prohibited within these protection zones in order to prevent contamination of drinking water. The immediate protection area encloses the surroundings of the wellhead, including the installations used for abstracting water. Depending on the type of aquifer, the outer boundary of this inner protection zone is defined at a fixed radial distance from the wellhead and can be easily marked. On the other hand, the intermediate and extended protection

areas are defined by the time it takes for groundwater to reach the well from the outer boundary of the protection zone. Consequently, the delineation of the two outer protection areas becomes a complex problem that often requires numerical modelling.

There are many computer programs that can be used to simulate groundwater flow to a well. Two-dimensional flow models commonly use horizontal discretization of the aquifer. Consequently, lateral variations of the aquifer properties are taken into account while the vertical sequence of high- and low-permeability layers within the aquifer system and the position of the screens of the well are neglected. Three-dimensional models allow a more precise spatial description of the aquifer, but on the other hand, the calculations involved are much more complex and time-consuming. Besides, in most cases there is not enough data available to describe the distribution of hydrogeological properties at the same level of accuracy as the spatial discretization of the model grid.

The vertical heterogeneity of the aquifer can be estimated from the lithological logs of the well. The position of the screens of a well is commonly known. As these parameters are important for calculating groundwater flow to a well and because they are available without any further investigations, it is, therefore, desirable to develop a model capable of an efficient simulation using lithological and well screen data. In axisymmetric flow modeling, it is assumed that groundwater flow to a well is radial. In this case, a cylindrical section of the aquifer can be discretized into horizontal layers and vertical shells around the well. Hence, vertical heterogeneity can be conveniently described whereas lateral variations in the hydrogeological properties are ignored. These restrictions fit well with the data that is available for most wells and make axisymmetric flow modeling an appropriate and suitable approach for simulating groundwater flow to a well.

Axisymmetric flow models are based on the assumption that groundwater flow to a well is radial, while the regional hydraulic gradient is negligible. The only driving force of flow is abstraction from the well. Disregarding lateral variations of hydrogeological properties, the resulting cone of depression is perfectly axially symmetric around the well. Thus, a vertical cross-section from the well to the outer limit of the cone of depression sufficiently describes the sloping hydraulic gradient around the well. Therefore, the three-dimensional drawdown can be determined by modelling the distribution of piezometric levels in two dimensions. Following the method of finite differences, the cross-sectional plane of the geological system is divided into cells by columns and rows. However, it is important to note that the cells do not represent rectangular sections of the aquifer like in common two-dimensional grids. As the columns of the axisymmetric grid are concentric cylindrical shells around the well, each cell represents a ring-shaped element. In the

neighborhoods of the pumping well, the hydraulic gradient increases and the cross-sectional area of flow decreases. Accordingly, finer discretization of the grid is required close to the well to accurately represent this increasing gradient. As an approximation of the distribution of hydraulic heads, the head value is calculated for the midpoint of each cell. Given that the rate of abstraction is constant, and flow is in a steady-state condition: inflow and outflow are balanced for each cell. The vertical exchange of groundwater between two cells can be determined by applying Darcy's Law. For calculating the horizontal flow of groundwater, the axial symmetry of the model has been taken into account by using the Dupuit-Thiem equation.

4. WELLHEAD PROTECTION AREAS APPLICATION TO A CASE STUDY AREA IN GOA, INDIA

4.1 Introduction

The developed methodology of determining the perimeters of protection zones was applied to a case study area by Krijgsman and Lobo-Ferreira (2001). For this, an area had to be chosen with enough reliable data available. The methodology is developed for use on unconfined aquifers, since these are the most directly vulnerable for pollutants entering from the surface.

First consideration was the Palmela County on the Setúbal Peninsula, near Lisbon, Portugal. This area consists roughly of a superficial (unconfined) aquifer and a deep confined aquifer, separated by an impermeable layer. There are numerous wells with hydrogeological data available, however all of them relate to the confined aquifer; no data are available of the superficial aquifer.

Other areas considered within Portugal were Torres Vedras and Ribeiras do Oeste. These areas displayed the same problem as with the Palmela County.

Another area, on which a research is being set up, is Goa, India, in cooperation with the University of Goa within the EU sponsored INCO-DEV COASTIN Project (Contract No IC 18-CT98-0296, http://www.dha.lnec.pt/nas/estudos/COASTIN.htm). LNEC received detailed data of an area of 8 by 15 km, consisting of a superficial aquifer. Data are available of all the needed parameters: water levels, aquifer thickness, screen length, extraction rates and porosity. Data are available of a maximum of 59 wells in this area; not all wells have data of each parameter.

Goa State, which has a land area of 3702 km², has a tropical climate with three seasons: a wet monsoon period from June to September, providing a precipitation of 2500 to 4300 mm, a winter season from October to January and a summer season from February to May. The population density of Goa is about 316/km² (Census 1991).

The case study area, which consists of a coastal area of 120 km², is situated in the northwestern corner of Goa in the district Bardez, having a population density of 717/km². The lithology consists of superficial laterites and sands, which are used as aquifers, underlain by precambriam metamorphic and crystalline rocks.

The studied area is rural, apart from the coastline, where many tourist resorts are located. The water demand is estimated on 150 liters per day in rural areas, while in tourist resorts this is about 500 liters (Chachadi and Raikar, 2000). To supply this demand, many large diameter wells are dug in the unconfined lateritic and sandy aquifers. A small part of the wells is in lithologies of (weathered) metagraywackes and phyllites. The well density is approximately 25 per km². The wells are normally shallow, not more than 15 m, with a diameter of up to 8 meters.

Available data:

- Water levels (taken on the same date), needed for deriving a hydraulic gradient (i): data are available on 57 wells for all seasons.

- Saturated aquifer thickness (b): data are available on 53 wells.

- Hydraulic conductivity (K): data, are available on 6 wells, ranging between 1.4 and 31 m/day.

- Extraction rate (Q): Data are available for two types of aquifers:

    For lateritic aquifers: Q varies between 86 and 216 m³/d, from which an average of 151 m³/d is taken.

    For sandy aquifers: Q varies between 155 and 259 m³/d, from which an average of 207 m³/d is taken.

- Effective porosity (n): data are available for 2 types of aquifers:

For lateritic aquifers: n varies between 0.20 and 0.30, from which an average of 0.25 is taken.
For sandy aquifers: n varies between 0.15 and 0.35, from which an average of 0.25 is taken.

4.2 Application of the methodology

4.2.1 Input data

For application of the methodology for delineation of wellhead protection areas, for the graphic outputs the program Surfer, version 6.01 of Golden Software is used.

As input, a data file is needed with information of coordinates of wells, together with data of i, b, K, Q and n.

From these data, continuous grids are extrapolated, all with the same dimensions to be able to make calculations with several grids.

- A hydraulic gradient, *i*, (rise over run) is derived from an extrapolated grid of water levels.

- For *b*, the saturated aquifer thickness is used. Using the screen length would be inadequate, since a large part of the extracted water in the wells originates from bottom inflow.

- For hydraulic conductivity, *K*, just six values are known, showing no clear correlation with lithology. From these six values a continuous grid is extrapolated.

- For extraction rate, *Q*, only two average values are known for the two lithologies. All wells with a lateritic lithology (37 wells) are given a value of 151 m³/d, all wells in a sandy lithology (15 wells) are given the value of 259 m³/d.

- For effective porosity, *n*, a value of 0.25 is taken as constant over the whole area. No grid is made since *n* has in this case a constant value.

Wells with data are well distributed throughout the whole area, except the south-western corner of the area, which is the Indian Ocean. Input data is shown in Figures 1- 4, and the wells are identified in Figures 1, 2 and 4 by the white dots. In Figure 3 the white dots represent the wells used for hydraulic conductivity assessment. There is however no topographical information available linked to the concerning area, because this information has been considered as classified. Therefore, no physical boundaries of the area are known. In this case this is no real obstacle, since this is only a demonstration of the use of the method on a non-hypothetical area.

4.2.2 Output of the methodology and conclusions of the regional 2D analysis

The three dimensions of the needed protection area have been calculated for three different seasons: the (dry) summer season, the wet season and the (dry) winter season. The differences in input between the seasons are the saturated thickness and the hydraulic gradient, both depending on the varying water levels. This could cause a difference in calculation of the protection area, depending on the season the data are used of. Figures 5-7 show the results obtained for the Summer Season.

The results obtained for the summer season, the wet season and the winter season, do not show significant differences per season in the dimensions of the needed protection areas.

The water levels can have a variation throughout the year of up to 6 m, but normally this is not more than 2-3 m. The hydraulic gradient derived from the water levels does not change much throughout the year. The maximum value is about 0.046 in the summer; in the wet season the maximum gradient is just slightly lower with a value of 0.043. Apparently the watertable rises or drops quite uniformly over the area with the change of season.

Due to the varying water levels, the saturated thickness will also vary throughout the year, but the effect on the needed protection area does not seem to be more than a few meters.

Whenever applying the methodology it should of course always be tried to estimate the maximum 50-day distance that is possible to occur in a certain time span. Theoretically, if calculating the upgradient protection distance it should therefore use, if available, the data of a season or year that create the highest hydraulic gradient, have the highest extraction rates or smallest aquifer thickness. The opposite is the case with the downgradient protection distance concerning the hydraulic gradient, thereby making it all more complex which data to use for which calculation.

In this case however, it proves not to result in considerable differences when using data of different seasons, which does not mean that this is always the case. After applying the methodology on more areas it will be possible to say more about this. As grid interpolation method in Surfer®, the default method kriging has been used. A different method could well give different results, as well as changing the options within the kriging method.

No physical boundaries are concerned. It is known that the south-western part of the case study area is the Indian Ocean. The exact location is not known; therefore it is treated as being land where data are missing and interpolated. In this case that does not matter much, since the area is only used for demonstrating the methodology.

Extrapolation of the grid of K-values is based on just six values. It would be a more logical approach to use a lithological map, from which a constant value of hydraulic conductivity per lithological unit is given. In this case there was no lithological map available.

A gradient is derived from data of levels in the wells, while the watertable in between the wells is probably higher. In other words, the gradient is derived from the maximum drawdown values, which are in the wells.

5. WELLHEAD PROTECTION ZONES IN THE VERTICAL DIMENSION

5.1 The computer program 'WellFlow'

In order to study groundwater flow to a well and to facilitate the delineation of wellhead protection areas espe-
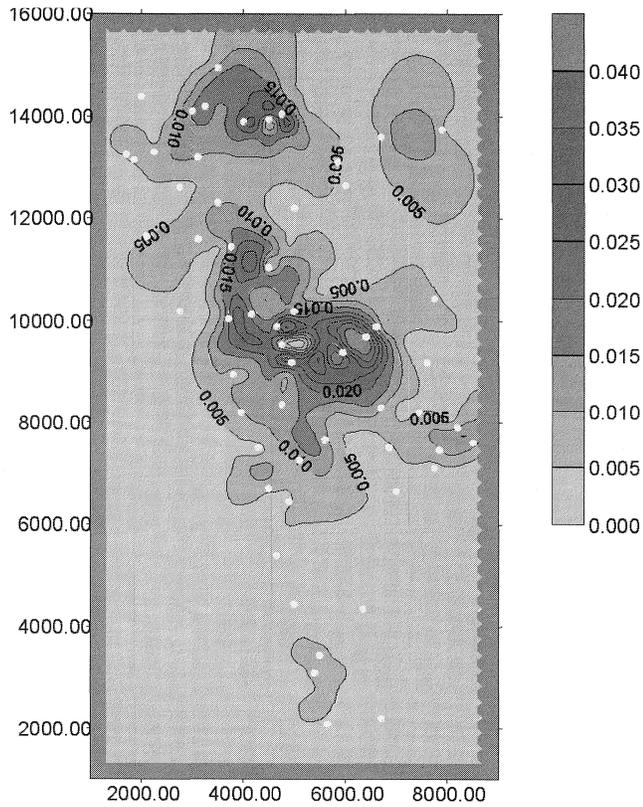
Fig. 1. Extrapolated grid of distribution of hydraulic gradient *i* in the wet season (07-28-2000).
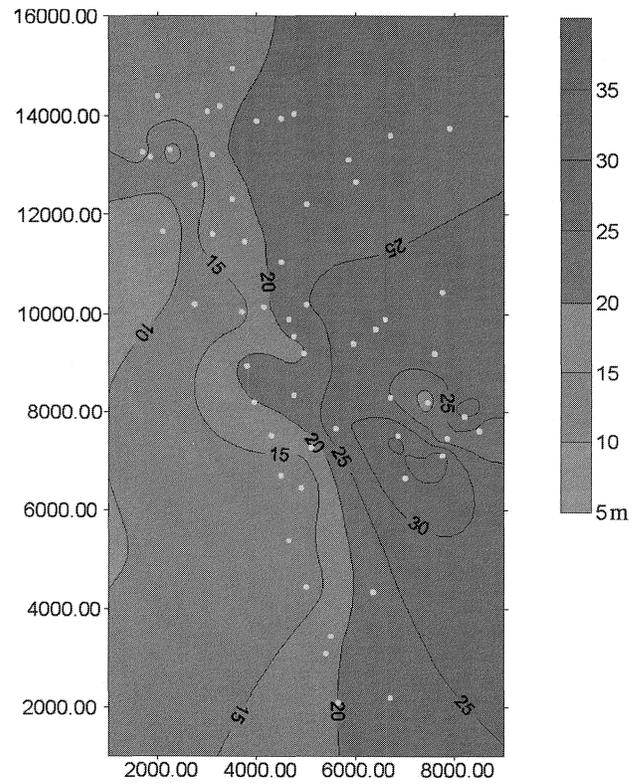
Fig. 2. Extrapolated grid of distribution of saturated aquifer thickness, *b*, for the wet season (07-28-2000)
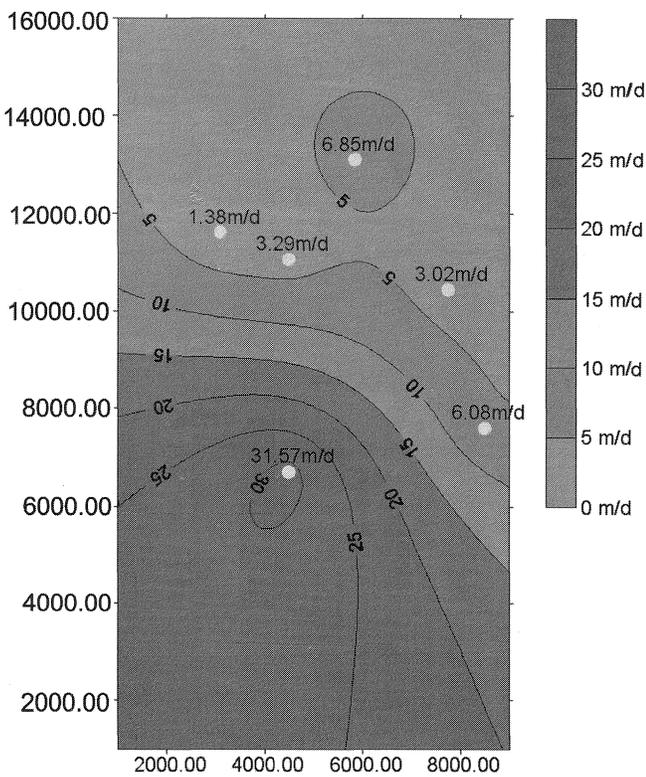
Fig. 3. Extrapolated grid of distribution of hydraulic conductivity, K.
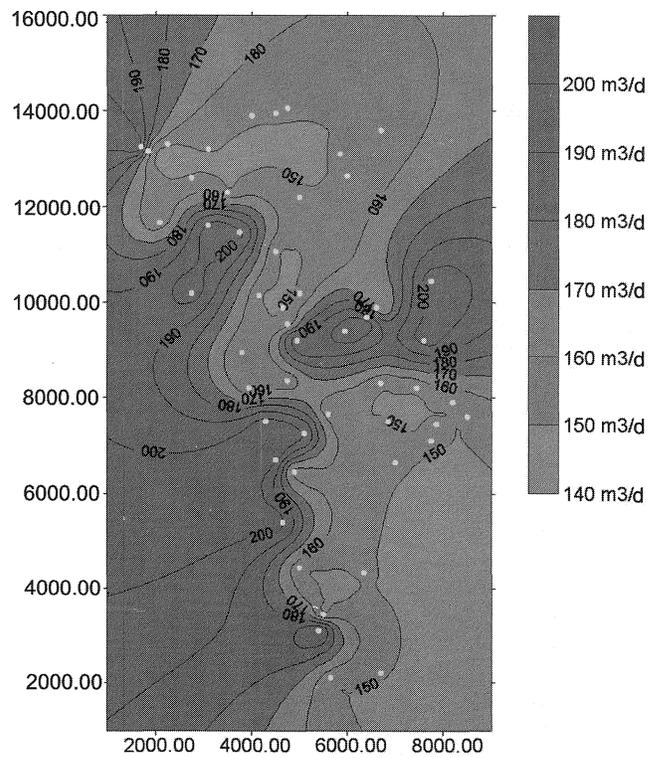
Fig. 4. Extrapolated grid of extraction rate or productivity, Q.
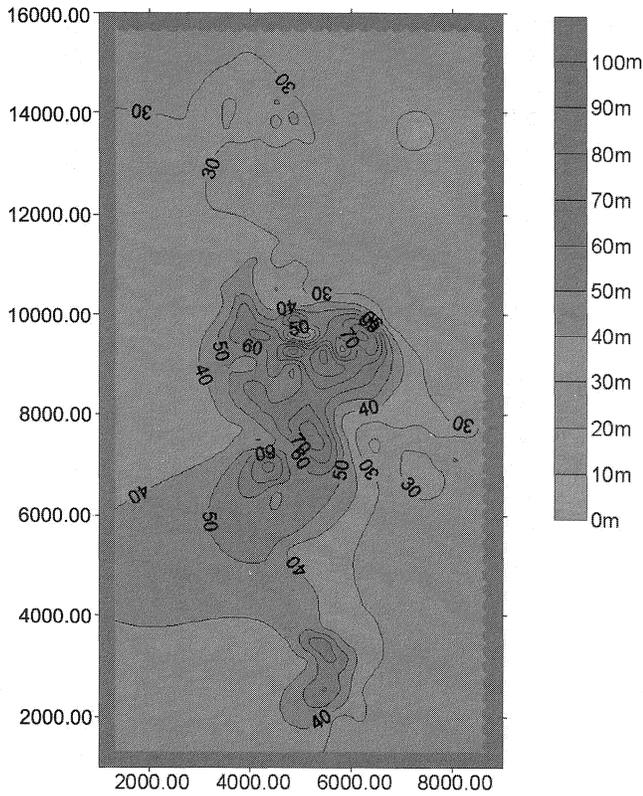
Fig. 5. Upgradient protection distance, as calculated with equation (2).
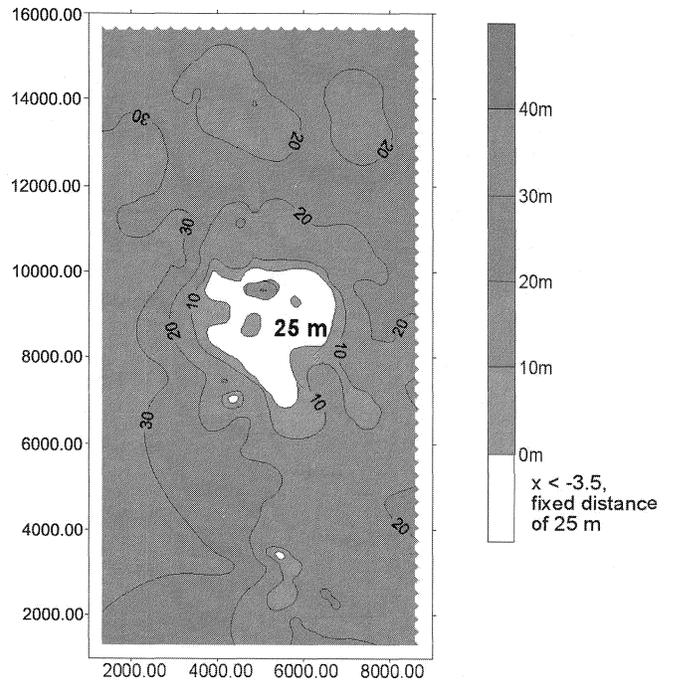
Fig. 6. Downgradient protection distance, as calculated with equation (3).
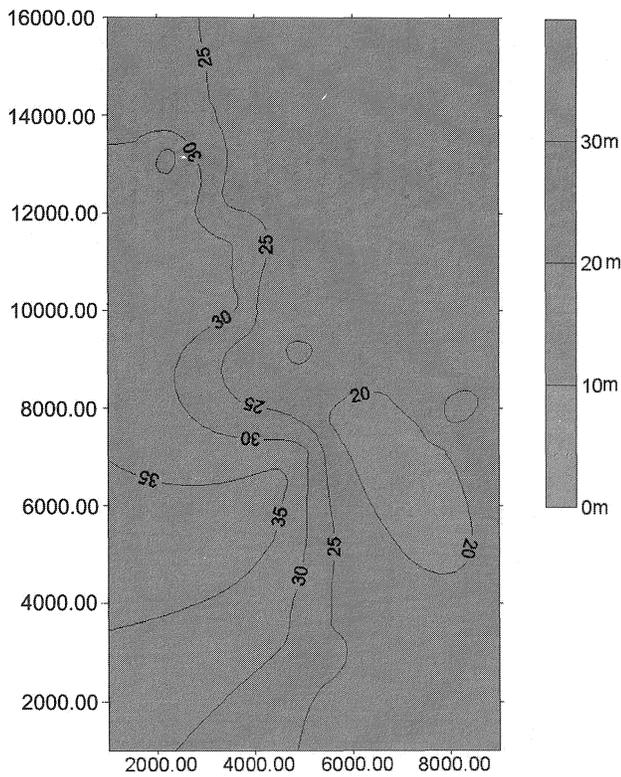
Fig.7. Protection distance perpendicular to direction of flow, as calculated with equation (4).
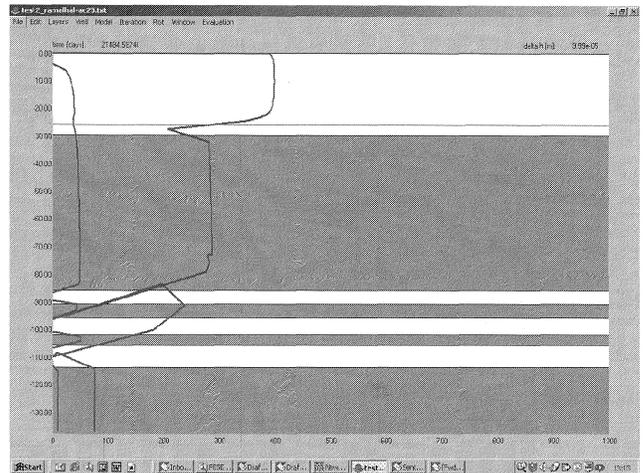
Fig. 8. Example of 50 and 3500 days isochrones with vertical influence (i.e. the stratification) of a potential pollutant, obtained with WellFlow model applied to a real pumping well located in Ramalhal, Portugal.

cially in multi-aquifer settings, the computer program 'WellFlow' was developed by Feseker and Lobo-Ferreira (2001). It is a user-friendly, menu- and mouse-driven stand-alone modeling tool for Windows and Mac OS. Steady-state groundwater flow to a well can be simulated by applying the method of finite differences, following an axisymmetric approach where a vertical cross-section of a cylinder is mod-

eled in 2D. The well is defined by abstraction rate and radius. Hydrogeological units (lithological data) at the position of the well are entered as horizontal layers that are homogenous and bear a constant thickness throughout the model area. A steady-state hydraulic head is assigned to each layer. The head value serves as a fixed head boundary condition on the outer model limit, while the flow between layers resulting from different steady-state heads is taken into account during iteration. Recharge from precipitation surplus can be defined for the top layer of the modeled sequence. The program uses this basic input data to automatically generate a finite difference grid. The distribution of hydraulic heads is solved numerically using an iteration process. Once the desired accuracy is reached, groundwater streamlines, and time of travel distances can be calculated by means of forward and backward particle tracking.

The program can be used to study the effects of different screening and vertical heterogeneity in layered aquifer systems on groundwater flow to a well. Flow to partially penetrating wells can be simulated. In contrast to horizontal two-dimensional models, WellFlow enables the user to calculate travel times for different depths of particle starting points. Thus, the protective effect of low-permeability layers above the aquifer can be examined when determining the size of protection zones. Furthermore, it is possible to apply WellFlow model even before a well is sunk in order to determine the most suitable design of the well as far as protection zones are concerned.

The isochronal line illustrates that the time it takes for a particle to reach the well strongly depends on the depth of the point where the particle enters the aquifer system. As a first test, WellFlow model has been applied to a well in Ramalhal, Portugal. The well is situated in the cretaceous Torres Vedras aquifer, approximately 50 km from Lisbon. It is 135 meters deep and consists of 13 screened and 15 unscreened intervals. The litholog comprises 27 different layers, ranging from clays to sands and conglomerates. By combining the information on the screening of the well with the litholog, the aquifer system can be divided into 8 unscreened and 6-screened layers. The hydrogeological properties of these 14 layers have been estimated from the petrography described in the lithology. The conductivity of the high permeability layers ranges from 1e-5 to 1e-4 m/s, whereas the conductivity of the low permeability layers varies between 1e-9 and 1e-8 m/s. As the model yields approximately the same relation between the abstraction rate and drawdown in the well as documented in the well-performance test, the chosen values for conductivity seem reasonable. For particle tracking, it is assumed that the effective porosities are 0.2 and 0.1, respectively. Figure 8 shows the layers used in the simulation and gives an overview of the distances corresponding to travel times of 50 days and of 3500 days for different depths of particle starting points. It is obvious that

the unscreened superficial aquifer and the uppermost aquitard protect the groundwater resources from pollutants injected close to ground surface. Above the first screen, flow velocities are so low that it takes a long time until groundwater from the two upper layers reaches the well. However, if there was a way for pollutants to quickly enter the deeper layers of the aquifer system, e.g. through an abandoned well or bore hole, they would reach the well much faster.

5.2 Conclusion of the axisymmetric radial model analysis

Axisymmetric models are well suited to modeling groundwater flow to a well, because all of the data that are already available for most wells may be included in the simulation. In contrast to horizontal two-dimensional models, both the vertical heterogeneity of multi layered aquifers and the position of the screens can be taken into account. Especially in the context of the delineation of wellhead protection areas, it seems important to include the vertical dimension in travel time calculations.

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